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Declaration

I hereby declare that this Master's thesis is completely my own work and that I used only the cited sources.

In Pilsen: …………………….

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ANOTAČNÍ LIST DIPLOMOVÉ (BAKALÁŘSKÉ) PRÁCE

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STRUČNÝ POPIS (MAX 10 ŘÁDEK) ZAMĚŘENÍ, TÉMA, CÍL POZNATKY A PŘÍNOSY	Tato diplomová práce se zaměřuje na tepelných strojů při různých účinných expanzích i kompresích. Účel tohoto zkoumání je definovat dopad těchto změn na termální efektivitu, výstup energie i entropii. Termodynamická analýza byla provedena pomocí matematických formulací.
KLÍČOVÁ SLOVA ZPRAVIDLA JEDNOSLOVNÉ POJMY, KTERÉ VYSTIHUJÍ PODSTATU PRÁCE	Tepelný stroj, entropie, výkon, účinnost, expanze, komprese.

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BRIEF DESCRIPTION TOPIC, GOAL, RESULTS AND CONTRIBUTIONS	This master thesis is focused on examine the performance of heat engines at different efficiencies of expansion and compression, to define the impact of these changes on the thermal efficiency, power output, and entropy. For this purpose a thermodynamic analysis is done by means of mathematical formulation.
KEY WORDS	Heat engine, entropy, efficiency, work output, expansion, and compression.

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List of Frequently Used Symbols

Symbol	Property
e	Specific flow exergy
$\dot{E}x$	Exergy destruction rate
h	enthalpy
m	mass
$\dot{m}$	mass flow rate
Q	Heat
$\dot{Q}$	Heat transfer rate
r	compression ratio
r_T	the ratio of the highest-to-lowest temperature of the cycle
r_{cut}	cut-off ratio
r_p	compression ratio
S	entropy
T	Temperature
V	volume
η_{th}	thermal efficiency
η_{th}	efficiency of compression
η_{th}	efficiency of expansion
W	work
$\dot{W}_{net}$	Power
c_P	Specific heat at constant pressure
c_V	Specific heat at constant pressure
γ	Specific heat ratio

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1. Introduction

Heat engines have been investigated by numerous scholars. Various optimization objectives were done to investigate the performance of well-known thermodynamic cycles including Brayton, Otto, and Diesel cycles. Many optimization criteria have been examined in past works as maximum efficiency, maximum work output, minimum entropy generation, and maximum ecological function.
The fact that the design point of maximum efficiency and maximum power output are identical is not true all the time, for example, for a regenerative Brayton-type heat engine, just at regenerative heat exchanger efficiency of 50% the design point of thermal efficiency and power output are identical [2, 8, 11].

The maximum efficiency optimization criteria means to get the maximum possible work per unit mass of fuel. While the maximum work output optimization criteria means to get the maximum possible power from engine regardless fuel consumption. There are many parameters define whether the optimization should be performed according to maximum power or maximum efficiency like constraints; the relative prices of power and fuel [7].

Another study was done by Salamon et al. [13, 14]. He tried to discuss and approve his idea that the optimization of heat engine should distinguish between the maximum work output and minimum entropy production, because they are different designs.

According to Bejan [9] the statement of Salamon et al. [13,14] is not always true. He depends on the simplest and oldest power plants model of Curzon and Ahlborn [16], Chambadal [17] and Novikov [18], and the equation of the efficiency at maximum power operation $\eta C_{-A} = 1 - \left(\frac{T_L}{T_H}\right)^{1/2}$ to prove that this efficiency could also be achieved by minimizing the entropy generation rate for those models of power plants.

Later Salamon et al. [7] have discussed the limitation of Bejan [9] for heat engines. Because according to him, just at certain design conditions there is equivalence between maximum work and minimum entropy production.

Leff [12] discussed that it is possible to obtain exactly or approximately value of the efficiency of the standard air-cycles including Otto, Diesel, Joule-Brayton and Atkinson, at maximum work output by using constant specific heats and applying in the Curzon–Ahlborn efficiency [16]

Leff [12] and Cruzon and Ahlbon [16] were assumed that the compression and expansion processes are isentropic, so the cycles are endo-reversible. Actually in practical applications it is not possible to avoid the internal irreversibilities.

An important definition of the production of entropy was by by Leff [10] and Lambert [5, 6] that it is it is the tendency of energy to spread out in space. So it is not a measure of disorder or losses in an energy system.

Thus, Y. Haseli [1] examined the performance of three common power cycles; Brayton, Otto and Diesel, at the condition of minimum entropy production. Taking into account the irreversibilities of the compression and expansion processes together with the irreversible heat transfer processes between the engine and the high and low temperature reservoirs due to the finite temperature differences, as it is depicted in Fig. 2. As a result of his work he found out that an engine designed based on a minimum entropy production criterion may operate at a low efficiency, lower than maximum achievable efficiency. So the minimization of entropy generation is not necessarily equivalent to minimization of energy losses taking place in real engines. The operational regime of a heat engine at minimum entropy production may be identical with that of maximum efficiency and maximum work output under certain circumstances; e.g. fixed heat input.

This study aims to examine the performance of these heat engines (Brayton, Otto and Diesel) at different efficiencies of expansion and compression, to define the impact of these changes on the thermal efficiency, power output, and entropy. The optimization of heat engines is done on the basis of thermodynamic principles. A thermodynamic analysis is done by means of mathematical formulation.

Another analysis has been done to compare the effect of increasing expansion efficiency verse the effect of increasing compression efficiency on thermal efficiency, power output and entropy for the three known cycles which are mentioned.

2. Thermodynamic Optimization Objectives

The optimization of heat engines on the basis of thermodynamic principles can be carried out using various objective functions. The most common objectives are as follows [3]:

1. Power (Work rate) output.
2. Thermal efficiency.
3. Second law efficiency.
4. Entropy generation due to the operation of engine.
5. Exergy destruction due to the operation of engine.
6. Thermo-economic.

Fig.1 illustrates a general model of a power generation plant. It interacts with **n** incoming and **m** outgoing flows, receives heat from p high temperature reservoir, and rejects heat to **q** low temperature reservoirs.

There exits **r** power consuming and s power producing compartments within the power plant model of Fig.1 [3].

If any of the first three objectives mentioned above is chosen as the design basis, the task of a designer is to maximize the selected objective function. On the contrary, if entropy generation or exergy destruction is considered as the optimization objective, in this case the task of a designer is to minimize the corresponding function. The optimization is done by taking into account that the optimization is usually carried out for steady-state operation of a heat engine.

2.1 Power Output

From the first law of thermodynamics, the net power of the engine at steady-state operation is determined as follows.

$$\dot{W}_{net} = \sum_{i=1}^{p} \dot{Q}_{H,i} - \sum_{j=1}^{q} \dot{Q}_{L,j} + \sum_{k=1}^{n} \dot{m}_k h_k - \sum_{k=1}^{n} \dot{m}_1 h_1 \tag{2.1}$$

Alternatively, one may evaluate the net power output of the engine by subtracting the total power requirement of the power consuming devices from the total amount of power produced by the power generating compartments.

$$\dot{W}_{net} = \sum_{i=1}^{s} \dot{W}_{P,i} - \sum_{j=1}^{r} \dot{W}_{C,j} \tag{2.2}$$

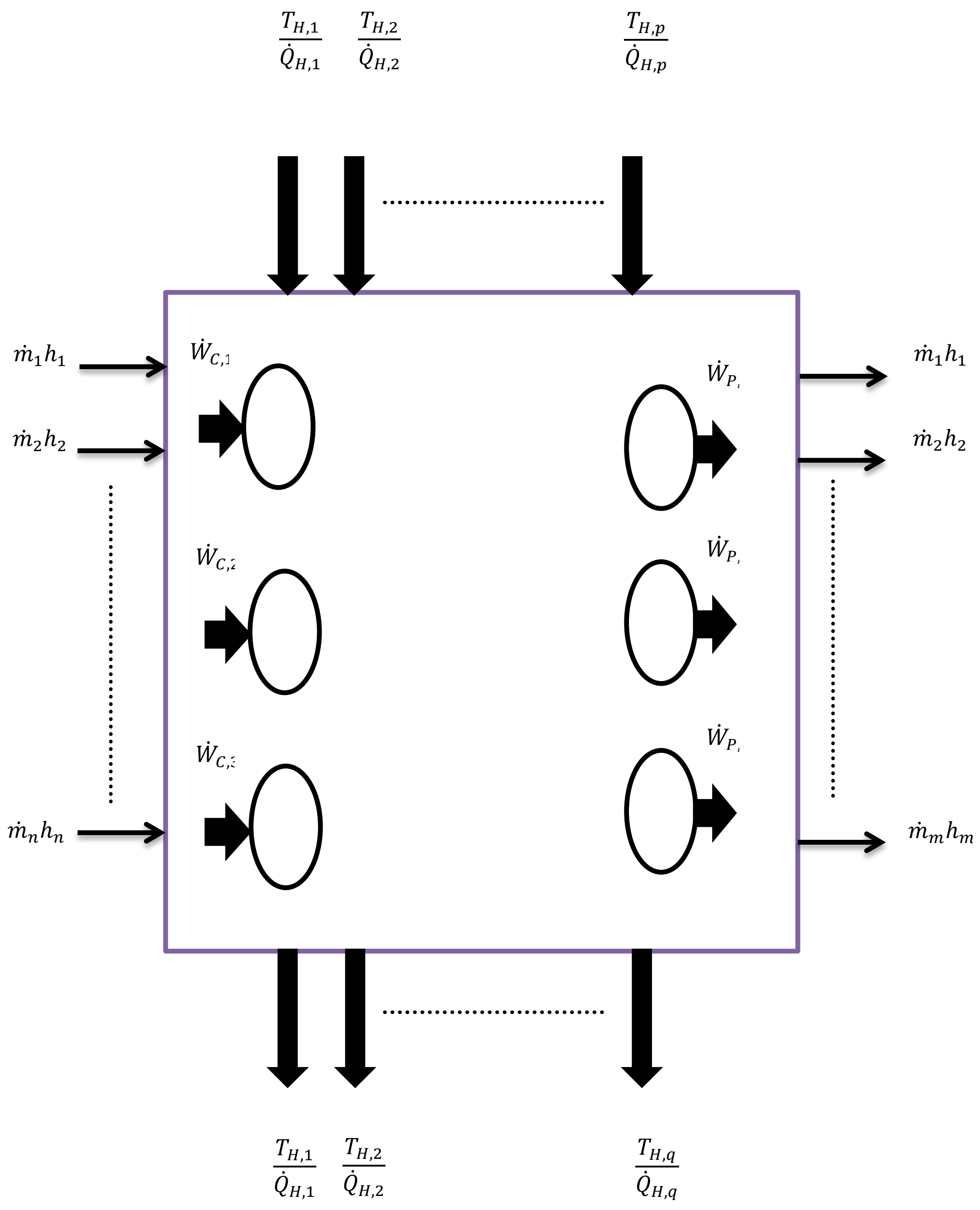

Figure 1 Schematic representation of a heat engine

2.2 Thermal Efficiency

The thermal or first law efficiency of a heat engine is defined as the ratio of the net power produced by the engine to the total amount of heat input to the system.

For the power plant model shown in Fig. 1, the total rate of heat input is

$$\dot{Q}_{H,tot} = \sum_{i=1}^{p} \dot{Q}_{H,i} \tag{2.3}$$

Thus, the thermal efficiency of the engine is defined as

$$\eta_{th} = \frac{\dot{W}_{net}}{\dot{Q}_{H,tot}} \tag{2.4}$$

2.3 Second Law Efficiency

The second law efficiency is described as the ratio of the thermal efficiency of a heat engine to the efficiency of a Carnot cycle operating between the same thermal reservoirs. Fig.1 shows the case of the power plant model of which communicates with multiple high and low temperature reservoirs, the Carnot efficiency may be defined as

$$1 - T_{L,min}/T_{H,max}$$

Where $T_{L,min}$ temperature of the coolest thermal reservoir.
$T_{H,max}$ temperature of the warmest thermal reservoir.

Thus, the second law efficiency of the engine shown in Fig.2 may be defined as

$$\eta_{th} = \frac{\eta_{th}}{\eta_{Carnot}} = \frac{\eta_{th}}{1 - T_{L,min}/T_{H,max}} \tag{2.5}$$

As $T_{L,min}$ and $T_{H,max}$ are fixed, the maximization of the second law efficiency would be identical to the maximization of the thermal efficiency.

2.4 Entropy Generation Rate

To determine the rate of entropy generation within a heat engine under steady-state operational condition, we apply the entropy balance equation for a control volume. Thus, the total rate of entropy produced within the system of Fig.2 takes the following form.

$$\dot{S}_{gen} = \sum_{j=1}^{q} \frac{\dot{Q}_{L,j}}{T_{L,j}} - \sum_{i=1}^{P} \frac{\dot{Q}_{H,i}}{T_{H,i}} + \sum_{l=1}^{m} \dot{m}_l s_l - \sum_{k=1}^{n} \dot{m}_k s_k \tag{2.6}$$

This equation denotes the total rate of entropy produced within the system of the Fig.2

2.5 Exergy Destruction Rate

The steady-state exergy rate balance for the heat engine model of Fig.2 is represented as follows.

$$\dot{E}x_{dest} = \sum_{i=1}^{p} \dot{Q}_{H,i}\left(1-\frac{T_0}{T_{H,i}}\right) - \sum_{j=1}^{q} \dot{Q}_{L,j}\left(1-\frac{T_0}{T_{L,j}}\right) + \sum_{k=1}^{n} \dot{m}_k e_k - \sum_{i=1}^{m} \dot{m}_l\, e_l - \dot{W}_{net} \tag{2.7}$$

Where: $\dot{W}_{net}$ is the net power output of the engine obtained from Eq. (2.1) or Eq. (2.2).

e is specific flow exergy defined as

$$(h-h_0) - T_0(s-s_0)$$

Bejan et al. [9] state that exergy destruction of a process is proportional to the entropy generation rate by a factor of environment temperature. So, minimization of exergy destruction would be identical to minimization of entropy generation rate.

To confirm the above statement, we will expand the right hand side of Eq. (2.7).

$$\begin{aligned}\dot{E}x_{dest} = {} & \sum_{i=1}^{p} \dot{Q}_{H,i} - \sum_{i=1}^{p} T_0\left(\frac{\dot{Q}_{H,i}}{T_{H,i}}\right) - \sum_{j=1}^{q} \dot{Q}_{L,j} + \sum_{j=1}^{q} T_0\left(\frac{\dot{Q}_{L,j}}{T_{L,j}}\right) - \dot{W}_{net} \\ & + \sum_{k=1}^{n} \dot{m}_k[(h-h_0) - T_0(s-s_0)]_k \\ & - \sum_{i=1}^{m} \dot{m}_l\, [(h-h_0) - T_0(s-s_0)]_l \end{aligned} \tag{2.8}$$

Once more we expand and rearrange the last equation

$$\begin{aligned}\dot{E}x_{dest} = {} & \sum_{i=1}^{p} \dot{Q}_{H,i} - \sum_{j=1}^{q} \dot{Q}_{L,i} - \dot{W}_{net} - \sum_{k=1}^{n} \dot{m}_k h_k - \sum_{l=1}^{m} \dot{m}_l h_l - T_0 \sum_{i=1}^{p}\left(\frac{\dot{Q}_{H,i}}{T_{H,i}}\right) \\ & + T_0 \sum_{j=1}^{q}\left(\frac{\dot{Q}_{L,j}}{T_{L,j}}\right) + T_0 \sum_{i=1}^{m} \dot{m}_l\, s_l - T_0 \sum_{i=1}^{n} \dot{m}_k\, s_k \\ & - h_0 \sum_{k=1}^{n} \dot{m}_k + h_0 \sum_{l=1}^{m} \dot{m}_l - T_0 s_0 \sum_{l=1}^{m} \dot{m}_l + T_0 s_0 \sum_{k=1}^{n} \dot{m}_k \end{aligned} \tag{2.9}$$

The principle of conservation of mass may be described as following

$$\sum_{i=1}^{m} \dot{m}_l = \sum_{k=1}^{n} \dot{m}_k \tag{2.10}$$

Taking into account Eq. (2.10), we find that the sum of the last four terms in Eq. (2.9) is zero. Also taking into account the Eq. (2.1), one may realize that the sum of the first five terms on the right hand side of Eq. (2.9) is zero.

As we know T_0 , h_0 , s_0 have fixed values which are related to the state of environment, so the Eq. (2.9) reduces to

$$\dot{E}x_{dest} = T_0 \left[\sum_{j=1}^{q} \left(\frac{\dot{Q}_{L,j}}{T_{L,j}} \right) - \sum_{i=1}^{p} \left(\frac{\dot{Q}_{H,i}}{T_{H,i}} \right) + \sum_{i=1}^{m} \dot{m}_l \, s_l - \sum_{i=1}^{n} \dot{m}_k \, s_k \right] \tag{2.1}$$

By combining Eqs. (2.6) and (2.11) we find

$$\dot{E}x_{dest} = T_0 \; \dot{S}_{gen} \tag{2.22}$$

2.6 Thermo-economic

Thermo-economics is the combination of thermodynamic principles and economic principles to provide a cost effective system in terms of design and operation.
The thermo-economic function is defined as the power output divided by the total cost plus the running and maintenance cost of the system [4].
As it was proposed in the previous researchers, the objective function of thermo-economic optimization is given by the following equation

$$F = \frac{P}{C_i + C_e + C_m} \tag{2.13}$$

Where; C_i annual investment cost
C_e energy consumption cost
C_m maintenance cost

2.7 Conclusion

As it was mentioned above the Thermodynamic optimization may be carried out by maximization of thermal efficiency, power output, or second law efficiency, or thermo-economic function; or through minimization of entropy generation rate or exergy destruction rate.

A design based on maximization of thermal efficiency is identical to a design on the basis of maximization of the second law efficiency. On the other hand, minimization of exergy destruction rate is equivalent to minimization of entropy generation rate. We are not going to consider the thermo-economic in this thesis, even it is important criteria.

Thus, only three optimization objectives including thermal efficiency, power output and entropy generation will be considered.

3. Mathematical formulation

The performance of irreversible Otto, Diesel and Brayton cycles is depicted in T–S diagram Fig.2. [1].

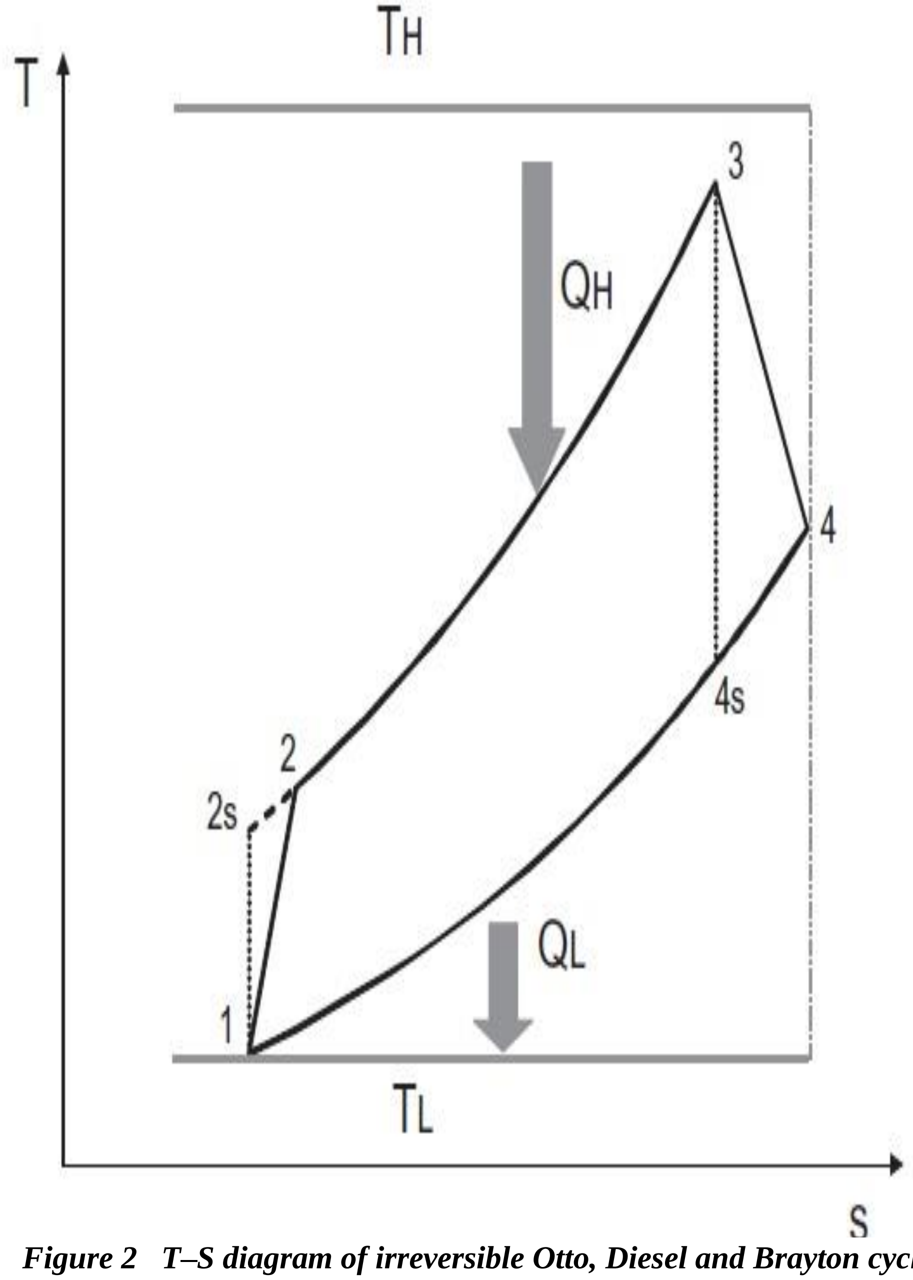

Figure 2 T–S diagram of irreversible Otto, Diesel and Brayton cycles

Line 1–2 represents irreversible compression process.
Line 3–4 represents irreversible expansion process.
Line 1–2s represents isentropic compression process.
Line 3–4s represents isentropic expansion process.

Line 2–3 represents a heat transfer process from the high temperature reservoir (T_H) to the engine at constant volume/pressure/pressure in the Otto/Diesel/Brayton cycle.

Line 4–1 shows the rejection of heat to the surrounding maintained at temperature T_L at constant volume/volume/pressure in the Otto/Diesel/Brayton cycle.

The isentropic efficiencies of the compression and the expansion processes are represented respectively as

$$\eta_{com} = (T_{2s} - T_1)/(T_2 - T_1)$$

$$\eta_{exp} = (T_3 - T_4)/(T_3 - T_{4s})$$

3.1 Otto cycle

First we have to determine temperatures T_2 and T_4 as functions of other operating parameters in order to evaluate the performance of the engine in terms of efficiency and work output [1].

$$(T_3/T_{4s}) = (T_{2s}/T_1) = r^{\gamma-1}$$

$$T_2 = T_1 + \frac{T_{2s} - T_1}{\eta_{com}} = T_1\left(1 + \frac{r^{\gamma-1} - 1}{\eta_{com}}\right) \tag{3.1}$$

$$T_4 = T_3 - \eta_{exp}(T_3 - T_{4s}) = T_3\left[1 - \eta_{exp}\left(1 - r^{\gamma-1}\right)\right] \tag{3.2}$$

Where; $r = V_1/V_2$ the compression ratio.

$\gamma = \frac{c_P}{c_V}$

By applying the first law we can determine the heat input and the heat output per unit mass of the air as following.

$$Q_H = c_V(T_3 - T_2) = c_V T_1\left(r_T - 1 - \frac{r^{\gamma-1} - 1}{\eta_{com}}\right) \tag{3.3}$$

$$Q_L = c_V(T_4 - T_1) = c_V T_1\left[r_T - 1 - \eta_{exp}\left(1 - r^{\gamma-1}\right)\right] \tag{3.4}$$

Where; r_T is defined as the ratio of the highest-to-lowest temperature of the cycle.

$$r_T = T_3/T_1$$

The work output

$$(W_{net})_{Otto} = Q_H - Q_L = c_V T_1 \left[r_T\, \eta_{exp}(1 - r^{\gamma-1}) - \frac{r^{\gamma-1} - 1}{\eta_{com}} \right] \tag{3.5}$$

The thermal efficiency

$$\eta_{Otto} = \frac{(W_{net})_{Otto}}{Q_H} = \frac{r_T\, \eta_{exp}\eta_{com}(1 - r^{1-\gamma}) - (r^{\gamma-1} - 1)}{(r_T - 1)\eta_{com} - (r^{\gamma-1} - 1)} \tag{46}$$

Entropy is generated due to four irreversible processes:

- compression process (path 1–2),
- heat transfer to the engine (path 2–3),
- expansion process (path 3–4),
- heat rejection from the engine to the ambient (path 4–1).

Then total entropy production associated with the operation of the engine is gives as following

$$S_{gen} = \frac{Q_L}{T_L} - \frac{Q_H}{T_H} \tag{3.7}$$

Then by Substituting Eqs. (3.3) and (3.4) into Eq. (3.7) we get

$$(S_{gen})_{Otto} = c_V \left\{ (r_T - 1)(1 - \pi) - r_T\, \eta_{exp}(1 - r^{\gamma-1}) + \frac{r^{\gamma-1} - 1}{\eta_{com}}\, \pi \right\} \tag{3.8}$$

Where; $\pi = T_L/T_H$ (In the present analysis $T_L = T_1$)
We apply $(\partial S_{gen}/\partial r) = 0$ in order to minimize the total entropy generation,

$$(r)_{S_{gen,min}} = \left(\frac{r_T}{\pi} \eta_{exp}\eta_{com} \right)^{\frac{1}{2\gamma-2}} \tag{3.9}$$

Fig.3 presents the work output versus the compression ratio at practical values of the compressor and the turbine efficiencies.
The optimum pressure ratio leading to a maximum work output is obtained by solving

$$(\partial W_{net}/\partial r) = 0$$

This leads to:

$$(r)_{W_{max}} = \left(r_T\, \eta_{exp}\eta_{com} \right)^{\frac{1}{2\gamma-2}} \tag{3.10}$$

This results shows that the work output is zero at a certain compression ratio that is greater than $(r)_{W_{max}}$; which can be obtained by solving Eq. (3.5) with $(W_{net})_{Otto} = 0$

$$(\mathrm{r})_{\mathrm{W_{net=0}}} = \left(\mathrm{r_T}\ \eta_{\mathrm{exp}}\eta_{\mathrm{com}}\right)^{\frac{1}{\gamma-1}} = (r)^2_{\mathrm{W_{max}}} \tag{3.11}$$

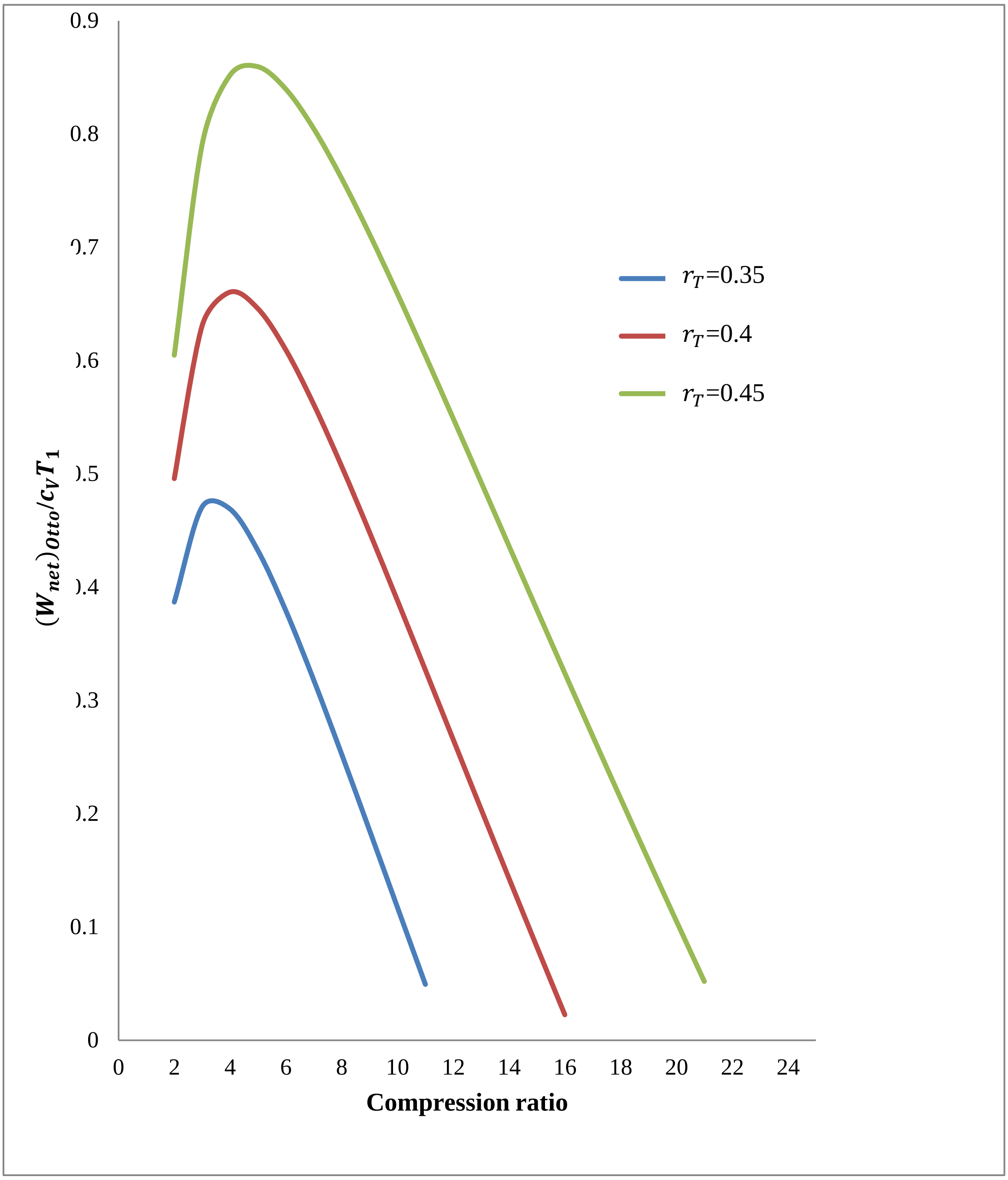

Figure 3 Variation of the dimensionless work output of otto cycle with pressure ratio at different values of r_T $\left(\eta_{exp} = 0.85,\ \eta_{com} = 0.9\right)$

From Eqs. (3.9) and (3.10)

$$(r)_{S_{gen,min}} = (r)_{W_{max}} \left(\frac{1}{\pi}\right)^{\frac{1}{2y-2}} \tag{3.12}$$

The last equation shows that the operational regimes at maximum work output and minimum entropy generation are different. And also by comparing Eqs. (3.9) and (3.10) It can be readily shown that $(r)_{S_{gen,min}} > (r)_{W_{net=0}}$. It means that the work output of the engine at the regime of minimum entropy production would be negative. The maximum compression ratio that the engine may approach is $(r)_{W_{net=0}}$. From this we can conclude that it is desirable for the Otto cycle to operate at minimum entropy generation, and the efficiency at maximum work would be more desirable.

3.2 Diesel cycle:

With the same procedures for diesel cycle, we can use Eq. (3.1) for determination of T_2 and T_4 is obtained as follows.

$$T_4 = T_3\left\{1-\eta_{exp}\left[1-\left(\frac{1}{r_{cut}}\right)^{1-\gamma}\right]\right\} \tag{3.13}$$

Where$1 < r_{cut} < r$, and r_{cut} denotes the cut-off ratio defined as $r_{cut} = V_3/V_2 > 1$.

It is related to the temperature ratio r_T as

$$r_T = r^{\gamma-1} r_{cut} \tag{3.14}$$

The efficiency of the Diesel cycle

$$(W_{net})_{Diesel} = c_V T_1\left\{(\gamma-1)(r_T-1) + \eta_{exp} r_T\left[1-\left(\frac{r}{r_{cut}}\right)^{1-\gamma}\right] - \frac{r^{\gamma-1}-1}{\eta_{com}}\gamma\right\} \tag{3.15}$$

The total entropy generation

$$\eta_{Diesel} = \frac{(\gamma-1)(r_T-1) + \eta_{exp} r_T\left[1-\left(\frac{r}{r_{cut}}\right)^{1-\gamma}\right] - \frac{r^{\gamma-1}-1}{\eta_{com}}\gamma}{\gamma\left(r_T-1-\frac{r^{\gamma-1}-1}{\eta_{com}}\right)} \tag{3.16}$$

$$\left(S_{gen}\right)_{Diesel} = c_V\left\{(r_T-1)(1-\gamma\pi) - \eta_{exp} r_T\left[1-\left(\frac{r}{r_{cut}}\right)^{1-\gamma}\right] + \frac{r^{\gamma-1}-1}{\eta_{com}}\gamma\pi\right\} \tag{3.17}$$

Maximization of the work output and minimization of the entropy generation result in the following optimum compression ratios.

$$(\mathrm{r})_{\mathrm{W_{max}}} = \left(r_T^{\gamma}\ \eta_{\mathrm{exp}}\eta_{\mathrm{com}}\right)^{\frac{1}{\gamma^2-1}} \tag{3.18}$$

$$(r)_{S_{gen,min}} = \left(\frac{r_T^{\gamma}}{\pi}\ \eta_{\mathrm{exp}}\eta_{\mathrm{com}}\right)^{\frac{1}{\gamma^2-1}} = (r)_{W_{max}}\left(\frac{1}{\pi}\right)^{\frac{1}{\gamma^2-1}} \tag{3.19}$$

As $\mathrm{r_{cut}} > 1$, combination of Equations. (26) and (31) leads to the following inequality.

$$\mathrm{r_T} > \frac{\eta_{\mathrm{exp}}\eta_{\mathrm{com}}}{\pi} \tag{3.20}$$

Which implies that for any $\mathrm{r_T}$ less than $\frac{\eta_{\mathrm{exp}}\eta_{\mathrm{com}}}{\pi}$, minimization of entropy generation would lead to an $\mathrm{r_{cut}}$ less than 1, which by definition is incorrect.

In a case of practical values we assume $\eta_{\mathrm{exp}} = 0.9$, $\eta_{\mathrm{com}} = 0.85$, and $\pi = 0.18$.

For $\mathrm{r_T} < 4.25\left(= 0.9 \times \frac{0.85}{0.18}\right)$, a design based on minimum entropy production criterion would require $\mathrm{r_{cut}} < 1$

3.3 Brayton cycle

Form the following relationship we can determine, the temperatures $\mathrm{T_2}$and $\mathrm{T_4}$ for the Brayton cycle

$$(T_3/T_{4s}) = (T_{2s}/T_1) = r_p^{\frac{\gamma-1}{\gamma}} \tag{3.21}$$

$$T_2 = T_1\left(1 + \frac{r_p^{\frac{\gamma-1}{\gamma}} - 1}{\eta_{com}}\right) \tag{3.22}$$

$$T_4 = T_3\left[1 - \eta_{exp}(1 - r_p^{\frac{\gamma-1}{\gamma}})\right] \tag{3.22}$$

$$T_4 = T_3\left[1 - \eta_{exp}(1 - r_p^{\frac{\gamma-1}{\gamma}})\right] \tag{3.23}$$

Where $r_p = P_2/P_1$

$$(W_{net})_{Brayton} = c_p T_1 \left[r_T\, \eta_{exp} \left(1 - r_p^{\frac{1-\gamma}{\gamma}} \right) - \frac{r_p^{\frac{\gamma-1}{\gamma}} - 1}{\eta_{com}} \right] \tag{3.24}$$

$$\eta_{Brayton} = \frac{r_T\, \eta_{exp} \left(1 - r_p^{\frac{1-\gamma}{\gamma}} \right) - \frac{r_p^{\frac{\gamma-1}{\gamma}} - 1}{\eta_{com}}}{(r_T - 1) - \frac{r_p^{\frac{\gamma-1}{\gamma}} - 1}{\eta_{com}}} \tag{3.25}$$

$$\eta_{Brayton} = \frac{r_T\, \eta_{exp} \left(1 - r_p^{\frac{1-\gamma}{\gamma}} \right) - \frac{r_p^{\frac{\gamma-1}{\gamma}} - 1}{\eta_{com}}}{(r_T - 1) - \frac{r_p^{\frac{\gamma-1}{\gamma}} - 1}{\eta_{com}}} \tag{3.26}$$

$$\left(S_{gen}\right)_{Brayton} = c_p \left\{ (r_T - 1)(1 - \pi) - \eta_{exp} r_T \left(1 - r_p^{\frac{1-\gamma}{\gamma}} \right) + \frac{r_p^{\frac{\gamma-1}{\gamma}} - 1}{\eta_{com}}\, \pi \right\} \tag{3.27}$$

To maximize the work output and minimize the entropy generation result in the following pressure ratio

$$\left(r_p\right)_{\mathrm{W_{max}}} = \left(r_T^{\gamma}\, \mathrm{\eta_{exp}} \mathrm{\eta_{com}}\right)^{\frac{1}{2\gamma-2}} \tag{3.28}$$

$$(r)_{S_{gen,min}} = \left(\frac{r_T^{\gamma}}{\pi}\, \mathrm{\eta_{exp}} \mathrm{\eta_{com}} \right)^{\frac{1}{\gamma^2-1}} \tag{3.29}$$

4. Numerical solutions

4.1 Impact of changing the efficiency of expansion (η_{exp}) on Otto cycle

In this section we investigate the impact of changing the efficiency of expansion η_{exp} on the thermal efficiency η_{Otto} , dimensionless work output $(W_{net})_{Otto}/c_V T_1$, and dimensionless entropy production $(S_{gen})_{Otto}/c_V$. The results are obtained for $r_T = 4$,$\pi = 0.18$, $\gamma = 1.4$, $\eta_{com} = 0.85$, $\eta_{exp} = (0.6, 0.7, 0.8, 0.85, 0.9, 1)$.

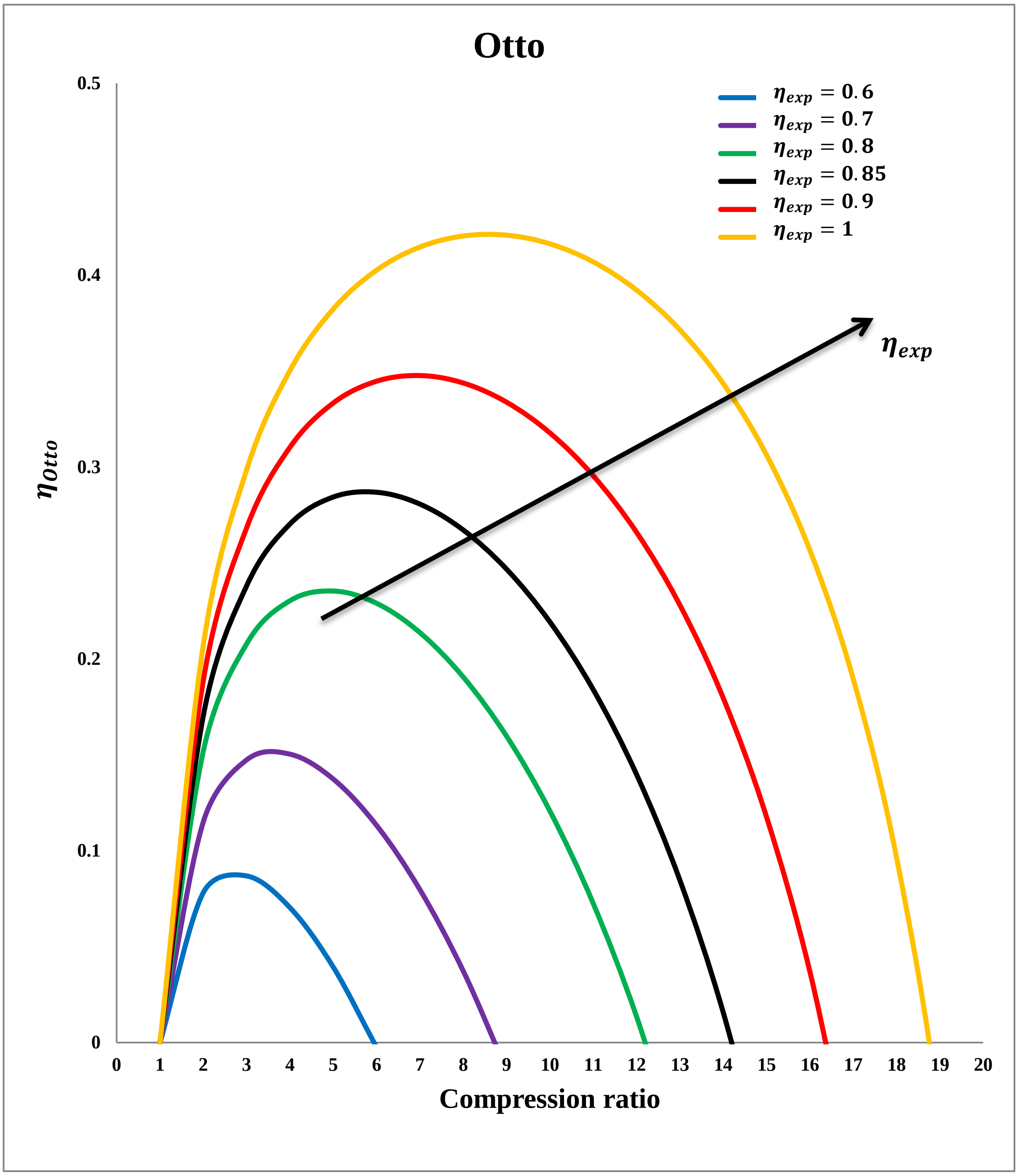

Figure 4 Variation of thermal efficiency η_{Otto} with compression ratio at different values of η_{exp}

As seen in a Fig.4 the thermal efficiency is zero at the compression ratio of 1, beyond which it increases with the compression ratio until it reaches the maximum value at a certain compression ratio for each value of η_{exp}, then it declines with an increase in the compression ratio until it reaches zero again at certain compression ratio. One may notice that the maximum thermal efficiency increases with the efficiency of expansion.

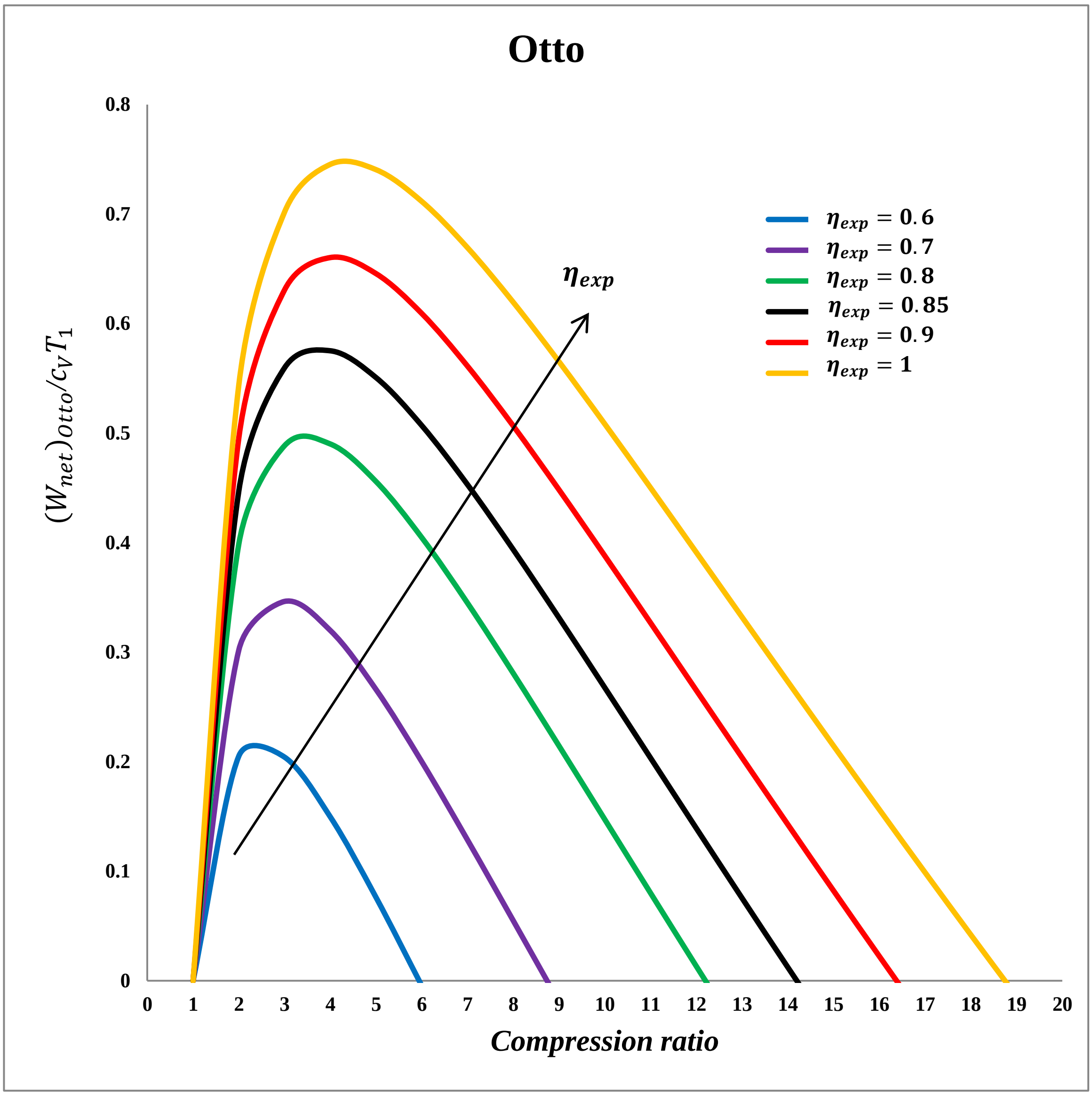

Figure 5 Variation of dimensionless work output $(W_{net})_{Otto}/c_V T_1$ with compression ratio at different values of η_{exp}

Fig.5 shows the variations of work output with compression ratio at different values of η_{exp} . At different values of η_{exp} the work output is 0 at the compression ratio of 1. Beyond which it increases with the compression ratio until it reaches the maximum value at a certain compression ratio for each value of η_{exp} , then it decline with an increase in the compression ratio until it reaches zero again at certain compression ratio.

From the last two figures one may notice that they have similar trends, and the changes of the work output are faster than the changes of thermal efficiency.

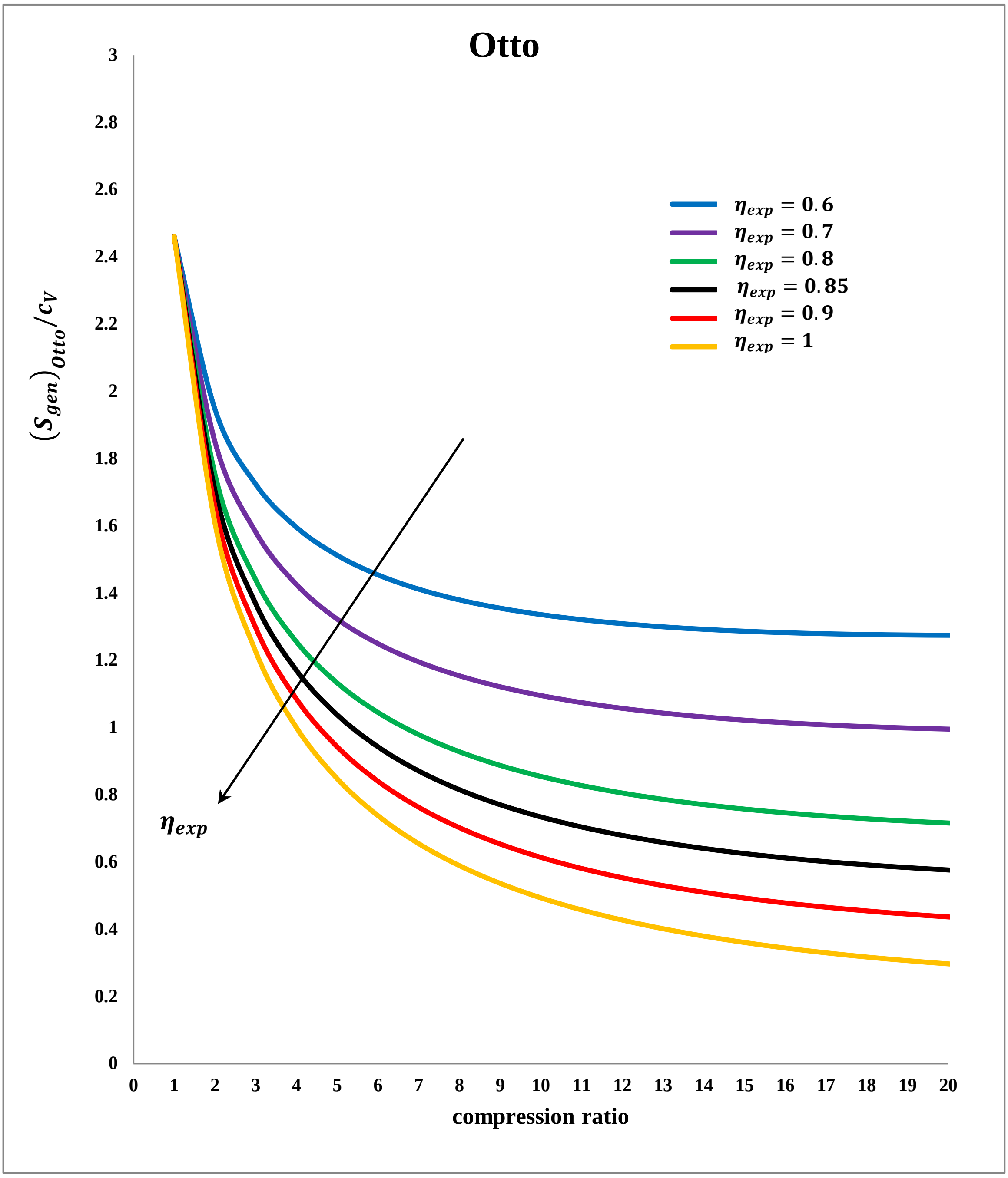

Figure 6 Variation of dimensionless entropy production $\left(S_{gen}\right)_{Otto}/c_V$ with compression ratio at different values of η_{exp}

The entropy changes take place in the opposite way as it is shown in Fig.6. The entropy has maximum value at compression ratio value of 1 for different values of η_{exp}, then it decreases with the compression ratio. The entropy values are almost identical at low pressure ratio, but at high pressure ratio there is an obvious discrepancies between them.

4.1.1 Maximum thermal efficiency and maximum work out put at different values of the efficiency of expansion η_{exp}

η_{exp}	η_{Otto_max}	$Pressure\ ratio$	$(S_{gen})_{Otto}/c_V$
0.6	0.0869	3	1.723
0.7	0.1503	4	1.425
0.8	0.2354	5	1.132
0.85	0.2869	6	0.942
0.9	0.3477	7	0.762
1	0.4209	8	0.589

Table 1 **Compression ratio and dimensionless entropy correspondin*g with Maximum thermal efficiency at different values of*** η_{exp}

η_{exp}	$(W_{net})_{max}/c_V T_1$	$Pressure\ ratio$	$(S_{gen})_{Otto}/c_V$
0.6	0.20525	2	1.947
0.7	0.34647	3	1.581
0.8	0.4902	4	1.255
0.85	0.57533	4	1.170
0.9	0.66046	4	1.085
1	0.74559	4	0.999

Table 2 Compression ratio and dimensionless entropy corresponding with Maximum dimensionless work out put at different values of η_{exp}

From the Tab. 1 we can find that the optimum compression ratio which corresponds to the maximum thermal efficiency increases with the efficiency of expansion. The entropy values are less than 1 when the efficiency of expansion is more than 80%.

Tab.2 shows that the optimum compression ratio which corresponds to maximum work output increases with the efficiency of expansion on low pressure ratio but their values are identical at high pressure ratio. The entropy values are almost equal or less than 1 when the efficiency of expansion is equal or more than 90%.

It is shown in the previous two tables that the maximum work output occurs at lower pressure ratio than maximum thermal efficiency for the same η_{exp}.

4.2 Impact of changing the efficiency of compression (η_{com}) on Otto cycle

For this case we undertake the same procedure, the results are obtained for $r_T = 4$, $\pi = 0.18$, $\gamma = 1.4$, $\eta_{exp} = 0.9$, at different values of $\eta_{com} = (0.6, 0.7, 0.8, 0.85, 0.9, 1)$.

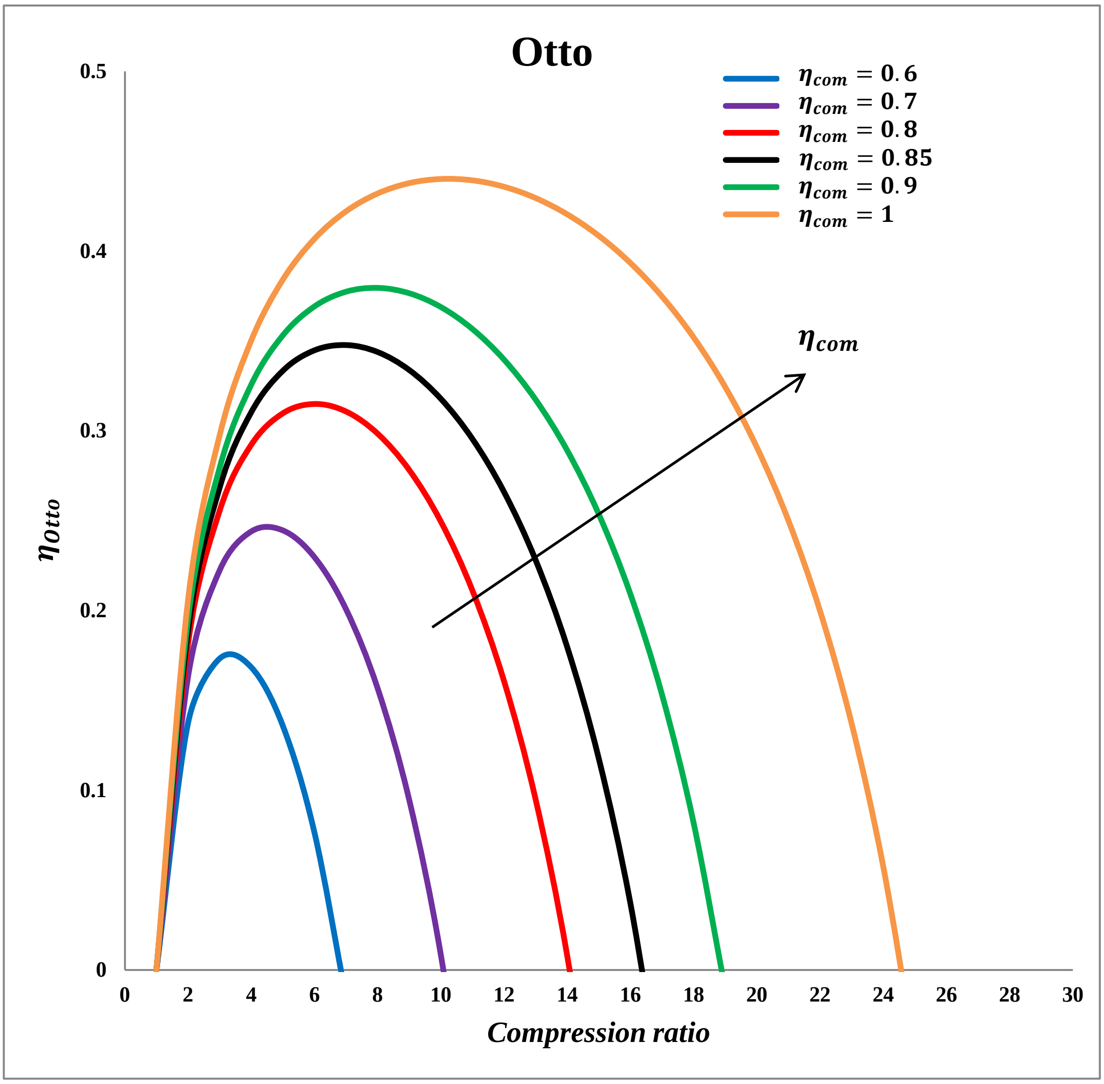

Figure 7 Variation of thermal efficiency η_{Otto} with compression ratio at different values of η_{com}

Fig. 7 shows that the thermal efficiency has similar trend at various compression‘s efficiency, it increases with the compression ratio until it reaches the maximum value at a certain compression ratio for each value of η_{com}, then it declines with an increase in the compression ratio until it reaches zero again at certain compression ratio for each value of η_{com}.

As seen in Fig.8 the work outputs is zero at the compression ratio of 1, beyond which it increases with the compression ratio until it reaches the maximum value, each at a certain compression ratio, then it decrease with an increase of the compression ratio to reach zero again each at certain compression ratio.

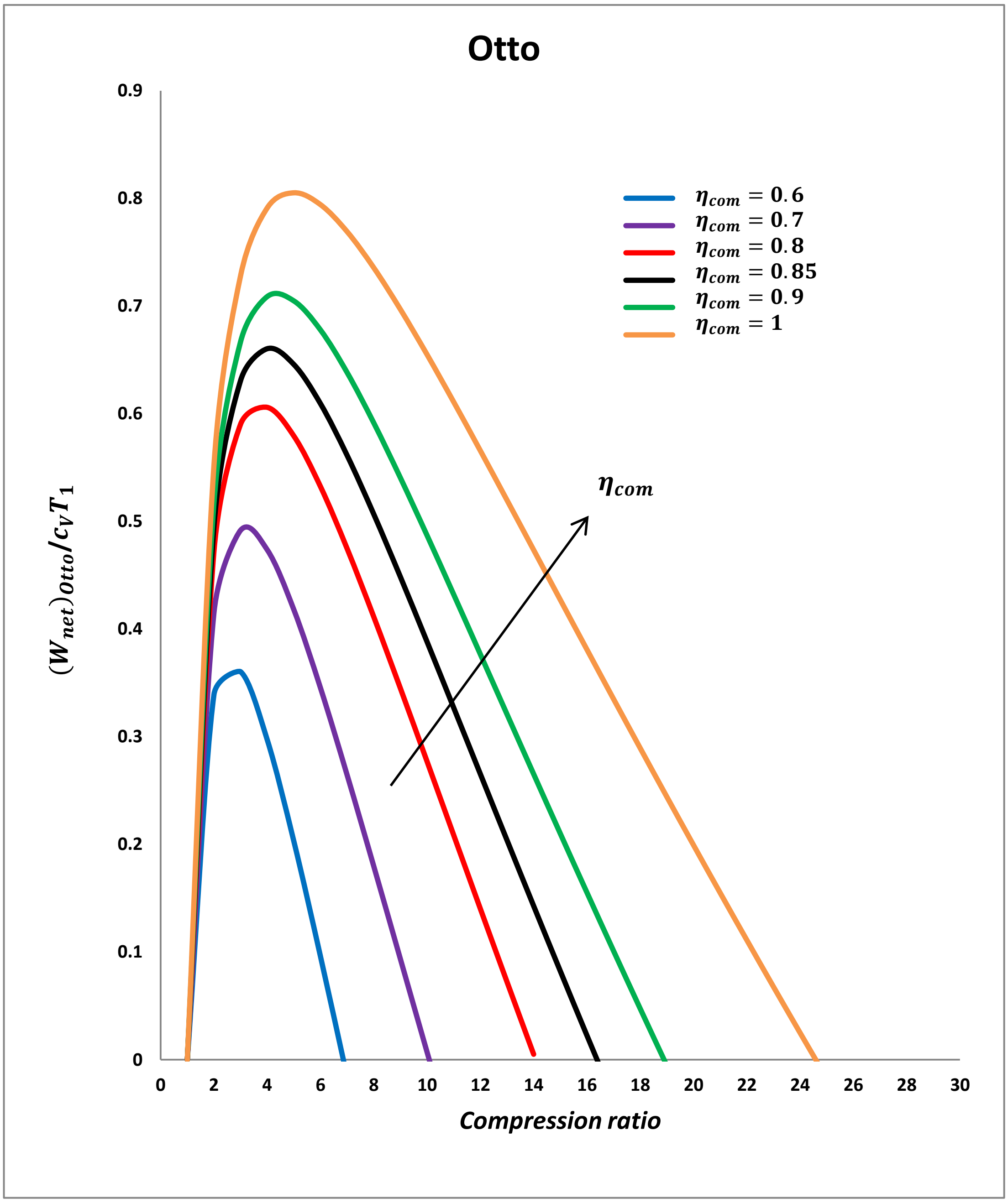

***Figure 8** Variation of dimensionless work output $(W_{net})_{Otto}/c_V T_1$ with compression ratio at different values of η_{com}*

The previous two figures show that the changes of thermal efficiency and the changes of work output at different values of η_{exp} or at different values of η_{com} have similar trends, each at certain compression ratio.

As seen in the Fig.9 entropy has maximum value at compression ratio value of 1 for different values of η_{exp} , then it decreases with the compression ratio. The entropy values are almost identical at low pressure ratio, but at high pressure ratio there is an obvious discrepancies between them.

At low pressure the entropy drops quickly at small increase in the compression ratio, in contrast the entropy slowly decreases slowly with the compression ratio on high pressure ratio.

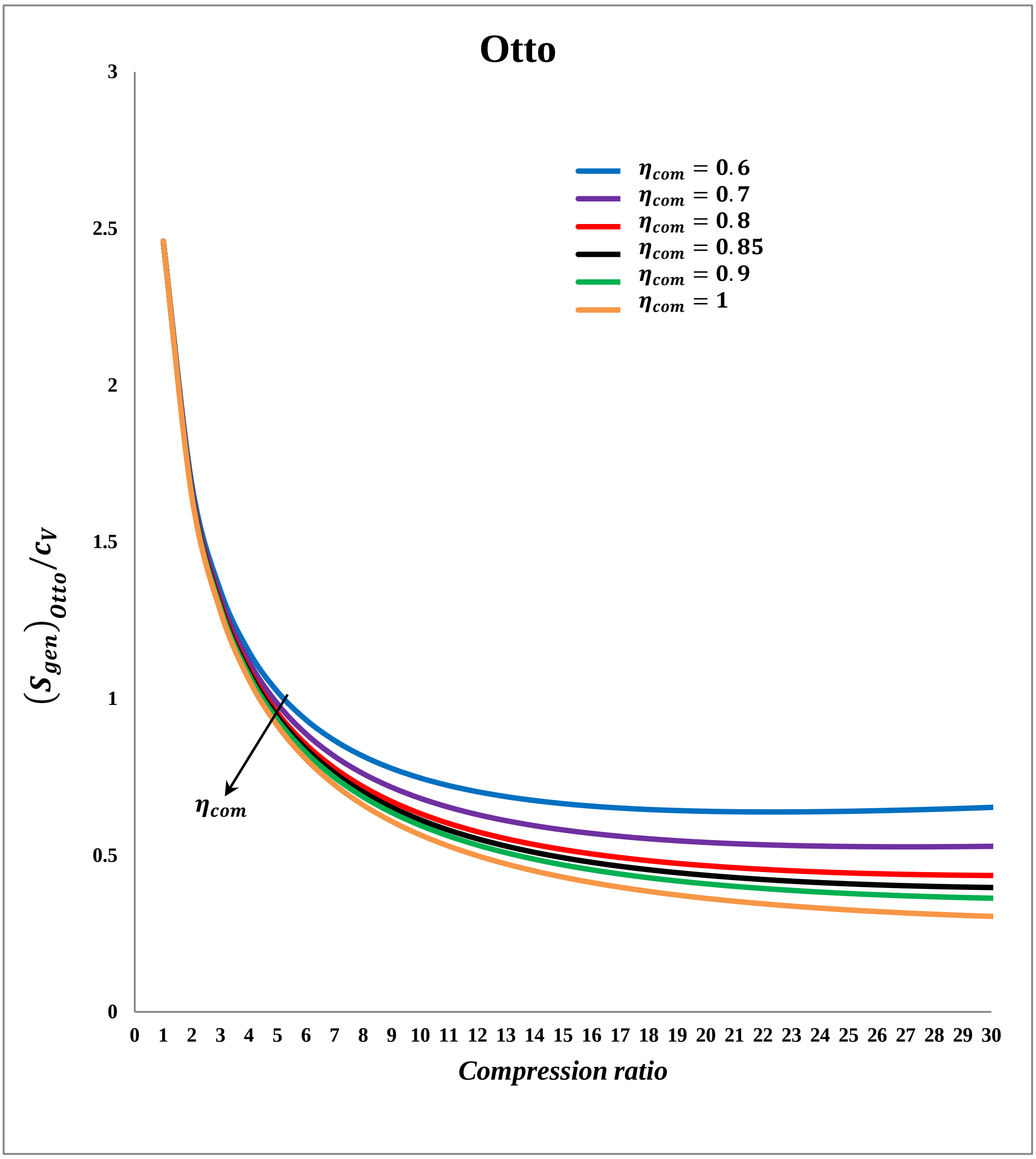

Figure 9 Variation of dimensionless entropy production $(S_{gen})_{Otto}/c_V$ with compression ratio at different values of η_{com}

4.2.1 Maximum thermal efficiency and maximum work out put at different values of the efficiency of compression η_{com}

η_{com}	η_{Otto_max}	$Pressure\ ratio$	$(S_{gen})_{Otto}/c_V$
0.6	0.173	3	1.345
0.7	0.245	5	0.983
0.8	0.315	6	0.854
0.85	0.348	7	0.762
0.9	0.380	8	0.686
1	0.440	10	0.565

Table 3 Compression ratio and dimensionless entropy corresponding with Maximum thermal efficiency at different values of η_{com}

η_{com}	$(W_{net})_{max}/c_V T_1$	$Pressure\ ratio$	$(S_{gen})_{Otto}/c_V$
0.6	0.360	3	1.345
0.7	0.492	4	1.322
0.8	0.606	4	1.094
0.85	0.660	4	1.085
0.9	0.709	4	1.076
1	0.805	5	0.914

Table 4 Compression ratio and dimensionless entropy corresponding with Maximum dimensionless work out put at different values of η_{com}

Tab. 3 shows that the optimum compression ratio which corresponds to maximum thermal efficiency increases with the efficiency of expansion.

Tab.4 shows that the optimum compression ratio which corresponds to maximum work output increases with the efficiency of expansion on lowest and highest pressure ratio but it has the same value between of them.

The work output reaches the maximum at compression ratio less than compression ratio for the maximum thermal efficiency at the same value of η_{com}.

For $\eta_{com} = 0.6$ the entropy and the compression ratio for the maximum thermal efficiency and maximum work output are identical. But the entropy is at the highest value.
For η_{com}>0.6 the maximum output takes place at lower compression ratio and higher entropy than maximum thermal efficiency.

4.3 Impact of changing the efficiency of expansion (η_{exp}) on Diesel cycle

For diesel cycle we applied the same procedures to study the impact of changing the efficiency of expansion on the thermal efficiency η_{Diesel} , dimensionless work output $(W_{net})_{Diesel}/c_V T_1$, and dimensionless entropy production $\left(S_{gen}\right)_{Diesel}/c_V$. The results are obtained for $r_T = 4$, $\pi = 0.18,$ $\gamma = 1.4$, $\eta_{com} = 0.85$, $\eta_{exp} = (0.6, 0.7, 0.8, 0.85, 0.9, 1)$.

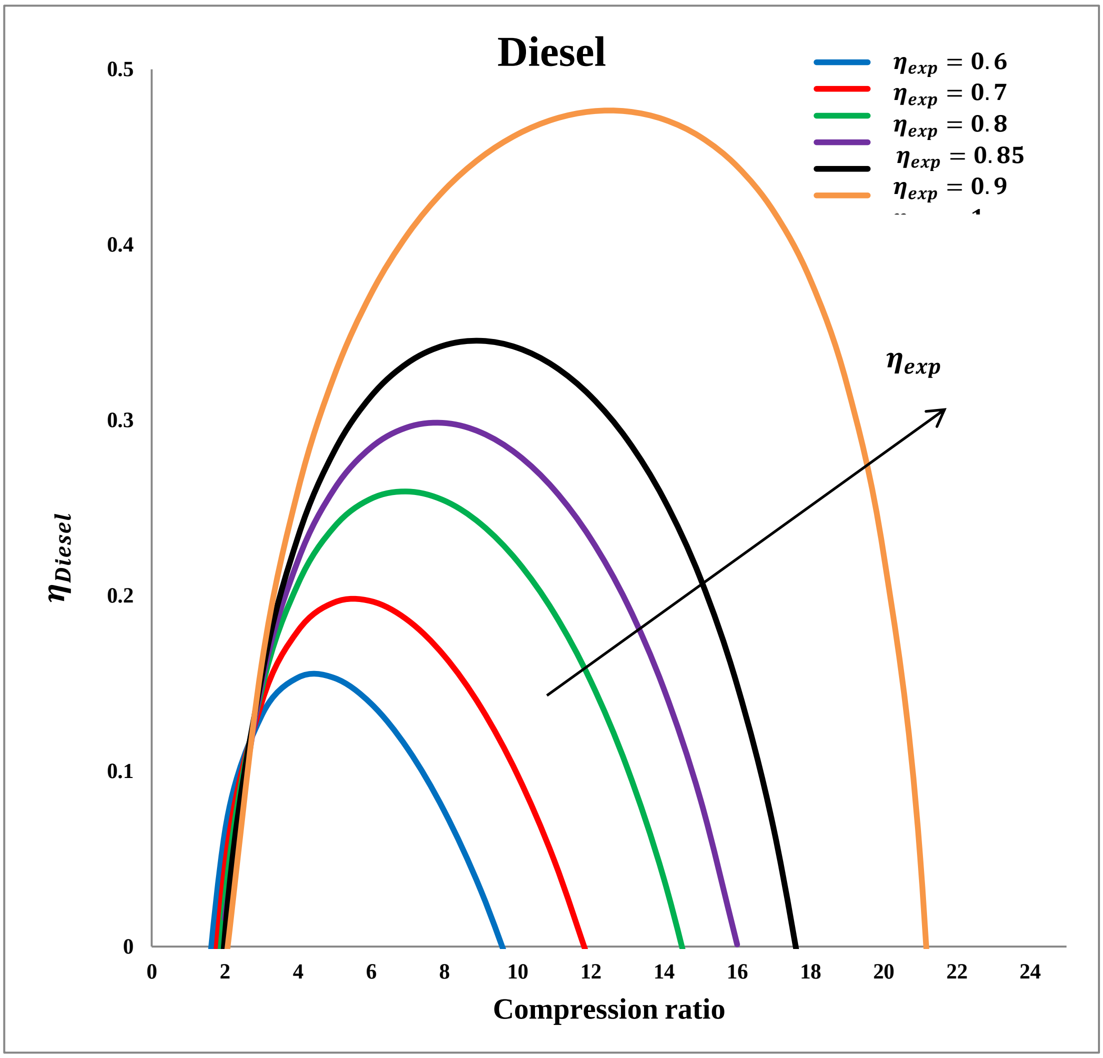

Figure 10 Variation of thermal efficiency η_{Diesel} with compression ratio at different values of η_{exp}

As seen in the last figure Fig.10 the thermal efficiencies are close to zero at the compression ratio of 2, beyond which they increase with the compression ratio till they become almost identical at compression ratio of 3, then they increase till they reach the maximum values, each at a certain compression ratio for each value of η_{exp} , then they decrease with the compression ratio till they reach zero again, each at certain compression ratio for each value of η_{exp}.

Fig.11 below shows that the work output is close to zero at the compression ratio of 2, and then they have similar trend as for the thermal efficiencies. The work outputs have almost identical values at low pressure ratio till the pressure ratio of 3, then an obvious discrepancies appear between them after pressure ratio of 3 for each value of η_{exp}.

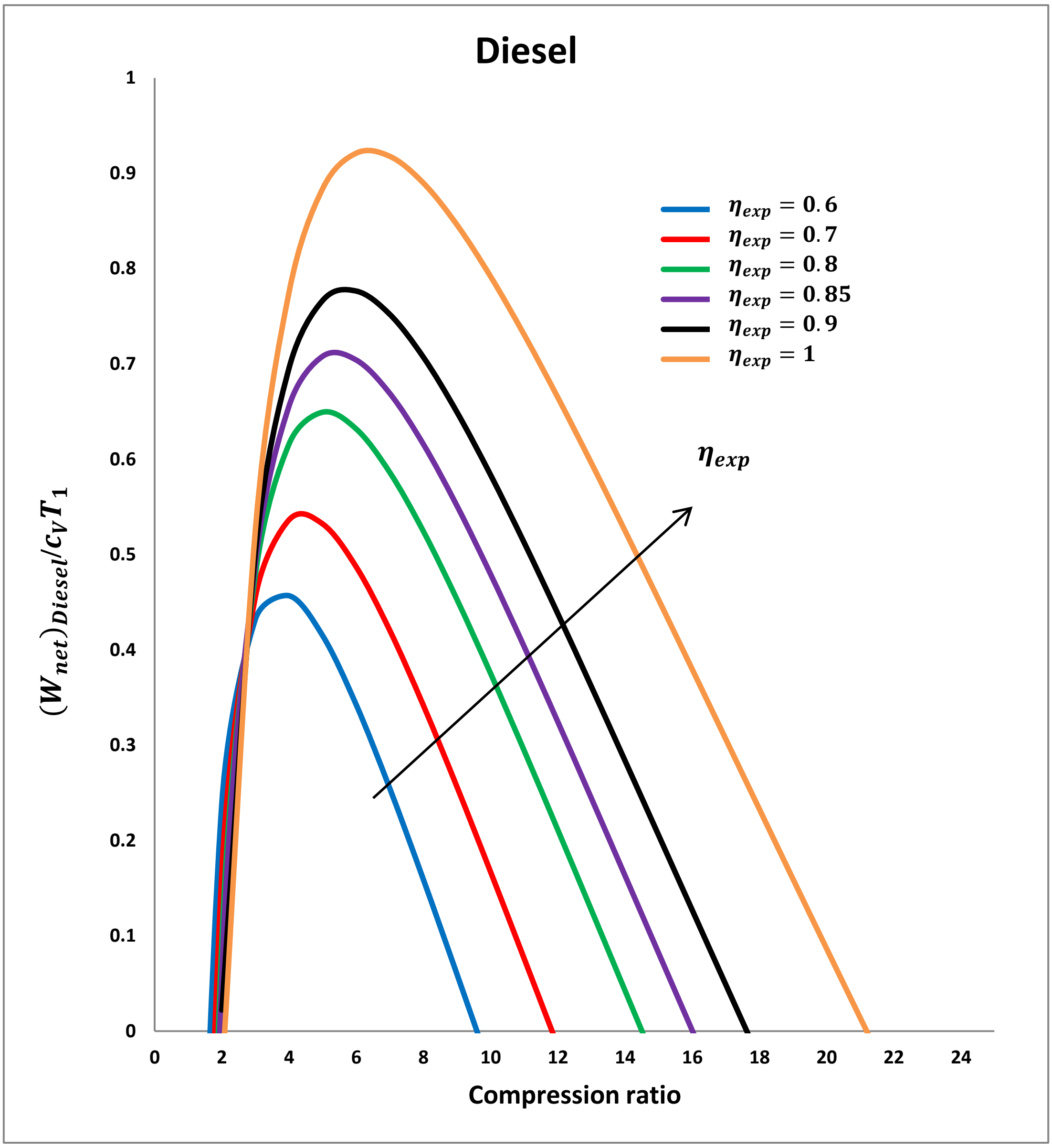

Figure 11 ***Variation of dimensionless work output $(W_{net})_{Diesel}/c_V T_1$ with compression ratio at different values of η_{exp}***

As seen in the Fig.12 maximum values of the entropy are at compression ratio of 1, then they decrease with the compression ratio till they reach almost identical values at pressure ratio of 3, then they decrease with the compression ratio; and an obvious discrepancies appear between them.

At low pressure ratio the entropy values are almost identical and they drop with a small increase of the compression ratio at different values of η_{exp}.

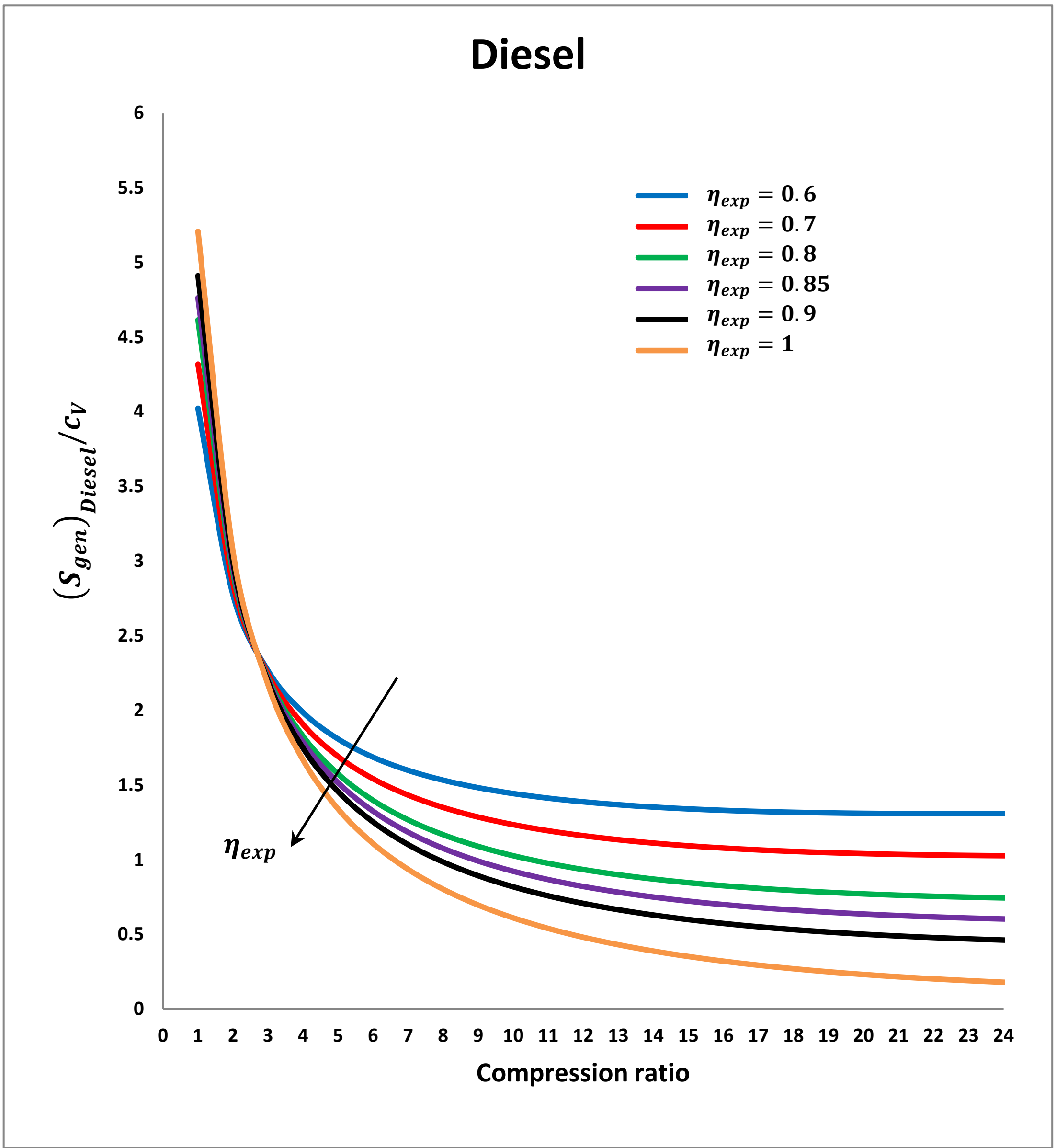

Figure 12 Variation of dimensionless entropy production $(S_{gen})_{Diesel}/c_V$ with compression ratio at different values of η_{exp}

4.3.1 Maximum thermal efficiency and maximum work out put for Diesel cycle at different values of the efficiency of expansion η_{exp}

η_{exp}	η_{Diesel_max}	$Pressure\ ratio$	$\left(S_{gen}\right)_{Diesel}/c_V$
0.6	0.153	4	0.801
0.7	0.197	6	1.542
0.8	0.259	7	1.267
0.85	0.298	8	1.076
0.9	0.345	9	0.893
1	0.476	13	0.431

Table 5 Compression ratio and dimensionless entropy corresponding with Maximum thermal efficiency at different values of η_{exp}

η_{exp}	$(W_{net})_{max}/c_V T_1$	$Pressure\ ratio$	$\left(S_{gen}\right)_{Diesel}/c_V$
0.6	0.4568	4	0.8011
0.7	0.5364	4	1.9067
0.8	0.6493	5	1.5742
0.85	0.7079	5	1.5156
0.9	0.7764	6	1.2527
1	0.9210	6	1.1080

Table 6 Compression ratio and dimensionless entropy corresponding with Maximum dimensionless work out put at different values of η_{exp}

From Tab.5 we find that the optimum compression ratio which corresponds to the maximum thermal efficiency obviously increases with the efficiency of expansion. Quite the opposite the changes of entropy. The entropy decreases with the efficiency of expansion. There is just one exception at the smallest value of expansion’s efficiency 60%.

Tab.6 shows that the optimum compression ratio which corresponds to maximum work output increases a little bit when the efficiency increases at least 20%. The entropy which corresponds to the maximum work output increases till the efficiency of expansion reaches 70% then it decreases with the increase of η_{exp}.

From the tables 5 and 6 it is shown that the work output reaches the maximum at compression ratio less than the compression ratio which corresponds to the maximum thermal efficiency at the same value of η_{exp}.

4.4 Impact of changing the efficiency of compression (η_{com}) on Diesel cycle

With the same procedures we studied the impact of changing the efficiency of compression on the thermal efficiency η_{Diesel} , dimensionless work output $(W_{net})_{Diesel}/c_V T_1$, and dimensionless entropy production $(S_{gen})_{Diesel}/c_V$. The results are obtained ($r_T = 4$,$\pi = 0.18$, $\gamma = 1.4$, $\eta_{exp} = 0.9$, $\eta_{com} = (0.6, 0.7, 0.8, 0.85, 0.9, 1)$.

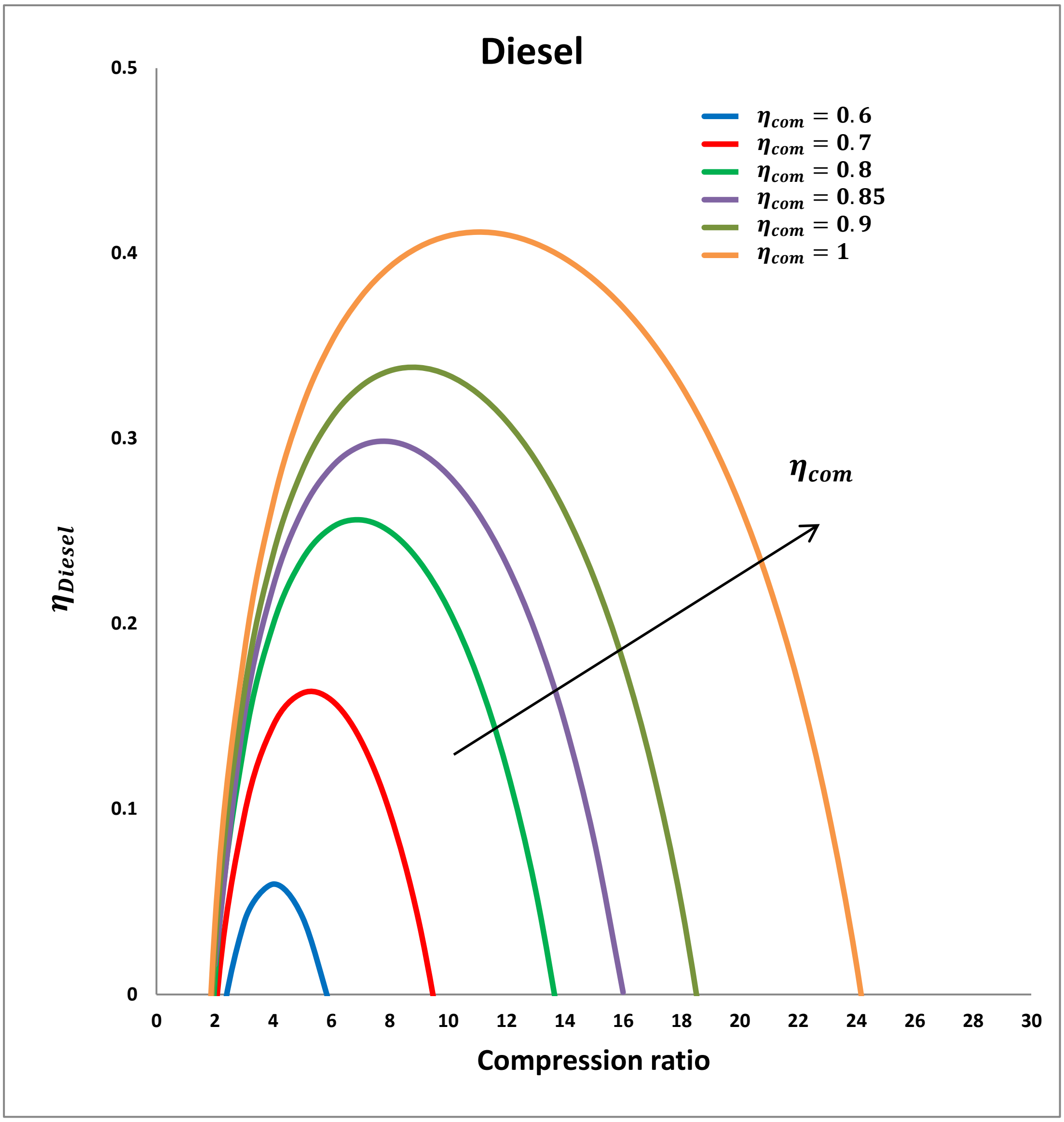

Figure 13 Variation of thermal efficiency η_{Diesel} with compression ratio at different values of η_{com}

Fig.13 shows the changes of the thermal efficiencies at different values of compression's efficiency. As we can see the efficiencies are close to zero at the compression ratio of 2 for all cases, and then they increase with the compression ratio till they reach the maximum values, each at a certain compression ratio, then they decrease with an increase in the compression ratio till they reach zero again each at certain compression ratio.

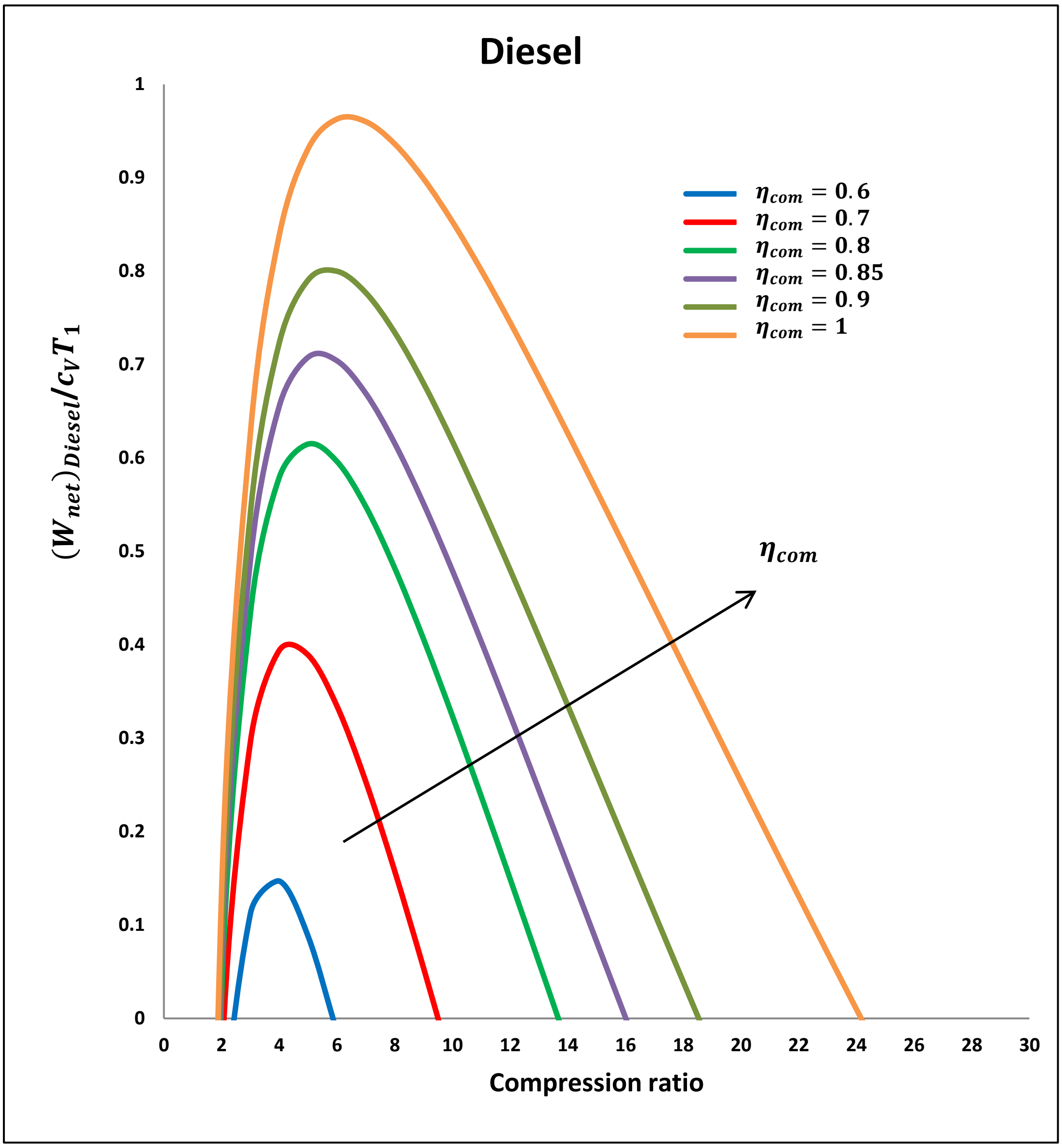

Figure 14 ***Variation of dimensionless work output*** $(W_{net})_{Diesel}/c_V T_1$ ***with compression ratio at different values of*** η_{com}

As seen in Fig.14 the work outputs variations are similar to the variations of thermal efficiencies at different values of η_{com}.

Variation of dimensionless entropy production are shown in Fig.15, when the compression ratio is close to 1 the entropy is at maximum values, and then these values of entropy decrease with the compression ratio for different η_{com}. The entropy values are almost identical at low pressure ratio, and at high pressure an obvious discrepancies appear between them.

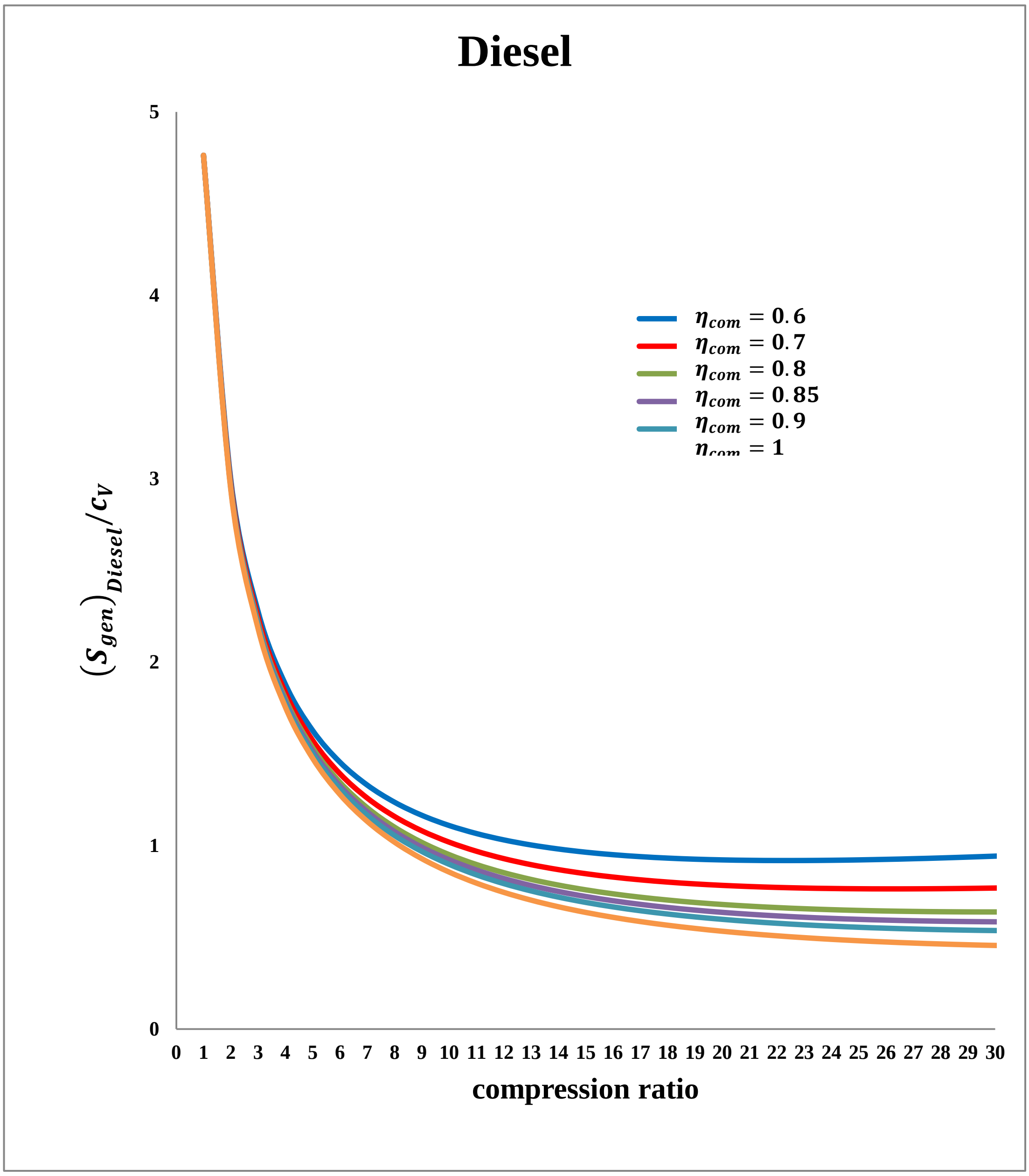

***Figure 15** Variation of dimensionless entropy production $(S_{gen})_{Diesel}/c_V$ with compression ratio at different values of η_{com}*

4.4.1 Maximum thermal efficiency and maximum work out put for Diesel cycle at different values of the efficiency of compression η_{com}

η_{com}	η_{Diesel_max}	$Pressure\ ratio$	$(S_{gen})_{Diesel}/c_V$
0.6	0.153	4	0.801
0.7	0.197	6	1.542
0.8	0.259	7	1.267
0.85	0.298	8	1.076
0.9	0.345	9	0.893
1	0.476	13	0.431

Table 7 Compression ratio and dimensionless entropy corresponding with Maximum thermal efficiency at different values of η_{com}

η_{com}	$(W_{net})_{max}/c_V T_1$	$Pressure\ ratio$	$(S_{gen})_{Diesel}/c_V$
0.6	0.4568	4	0.8011
0.7	0.5364	4	1.9067
0.8	0.6493	5	1.5742
0.85	0.7079	5	1.5156
0.9	0.7764	6	1.2527
1	0.9210	6	1.1080

Table 8 Compression ratio and dimensionless entropy corresponding with Maximum dimensionless work out put at different values of η_{com}

Tab. 7 and Tab. 8 show that the optimum compression ratio corresponding to maximum thermal efficiency and the maximum work output increases with the efficiency of compression. And the maximum power output occurs at a pressure ratio less than the one which corresponds to the maximum thermal efficiency.

For $\boldsymbol{\eta_{com}} = 0.6$ the entropy and the pressure ratio are identical for the maximum thermal efficiency and the maximum work output. Beyond this value of $\boldsymbol{\eta_{com}}$ the entropy declines and the maximum thermal efficiency and the maximum work output increase with the efficiency of compression each at certain pressure ratio.

4.5 Impact of changing the efficiency of expansion (η_{exp}) on Brayton cycles

We applied the same procedures on Brayton cycle to investigate the changes of the thermal efficiency η_{Otto} , dimensionless work output $(\mathrm{W_{net}})_{Brayton}/\mathrm{c_V T_1}$, and dimensionless entropy production $\left(\mathrm{S_{gen}}\right)_{Brayton}/\mathrm{c_V}$. The results are obtained for $r_T = 4, \pi = 0.18, \gamma = 1.4, \eta_{com} = 0.85$, $\eta_{exp} == (0.6, 0.7, 0.8 , 0.85, 0.9, 1)$.

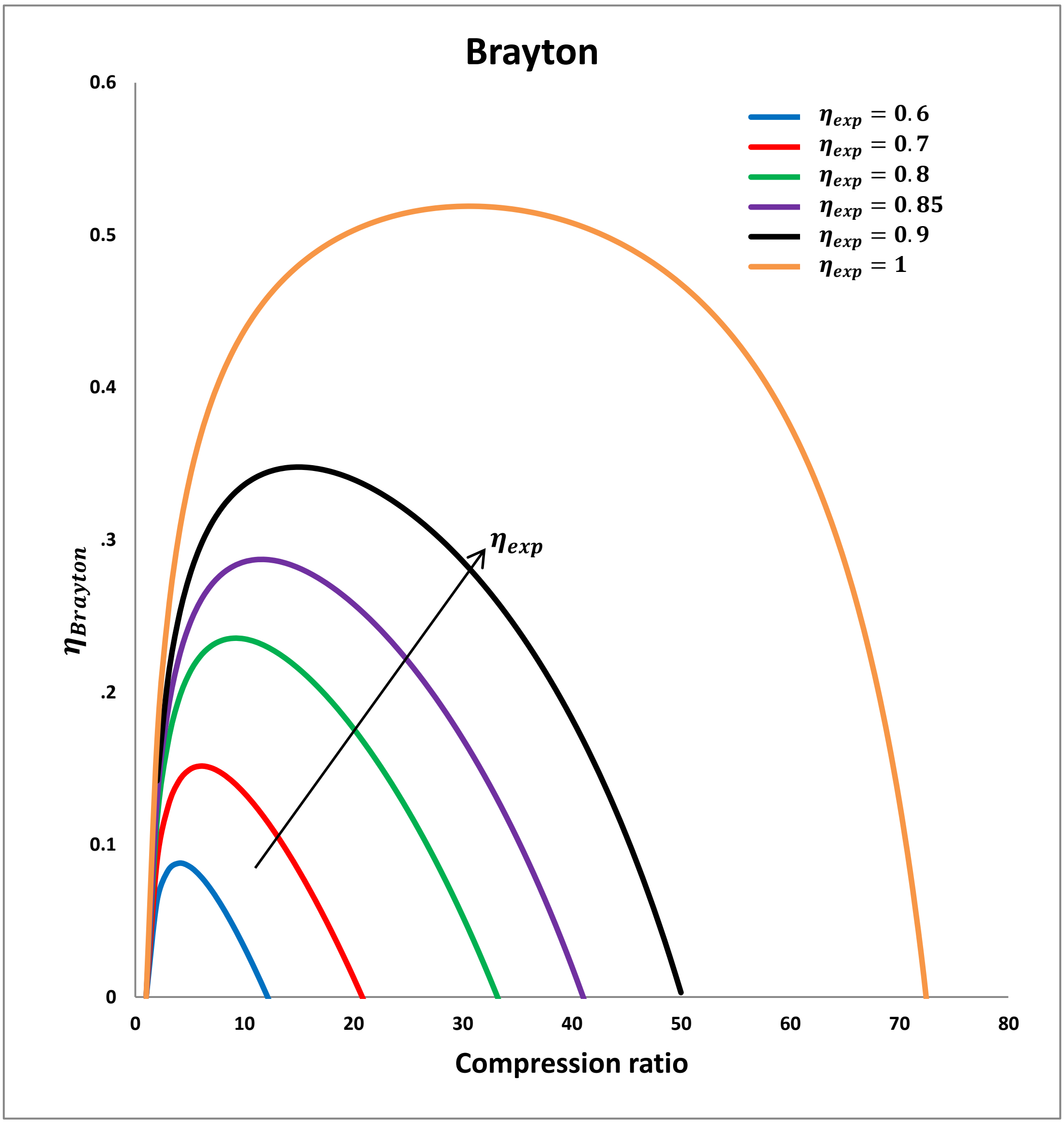

Figure 16 ***Variation of thermal efficiency*** $\boldsymbol{\eta_{Brayton}}$ ***with compression ratio at different values of*** $\boldsymbol{\eta_{exp}}$

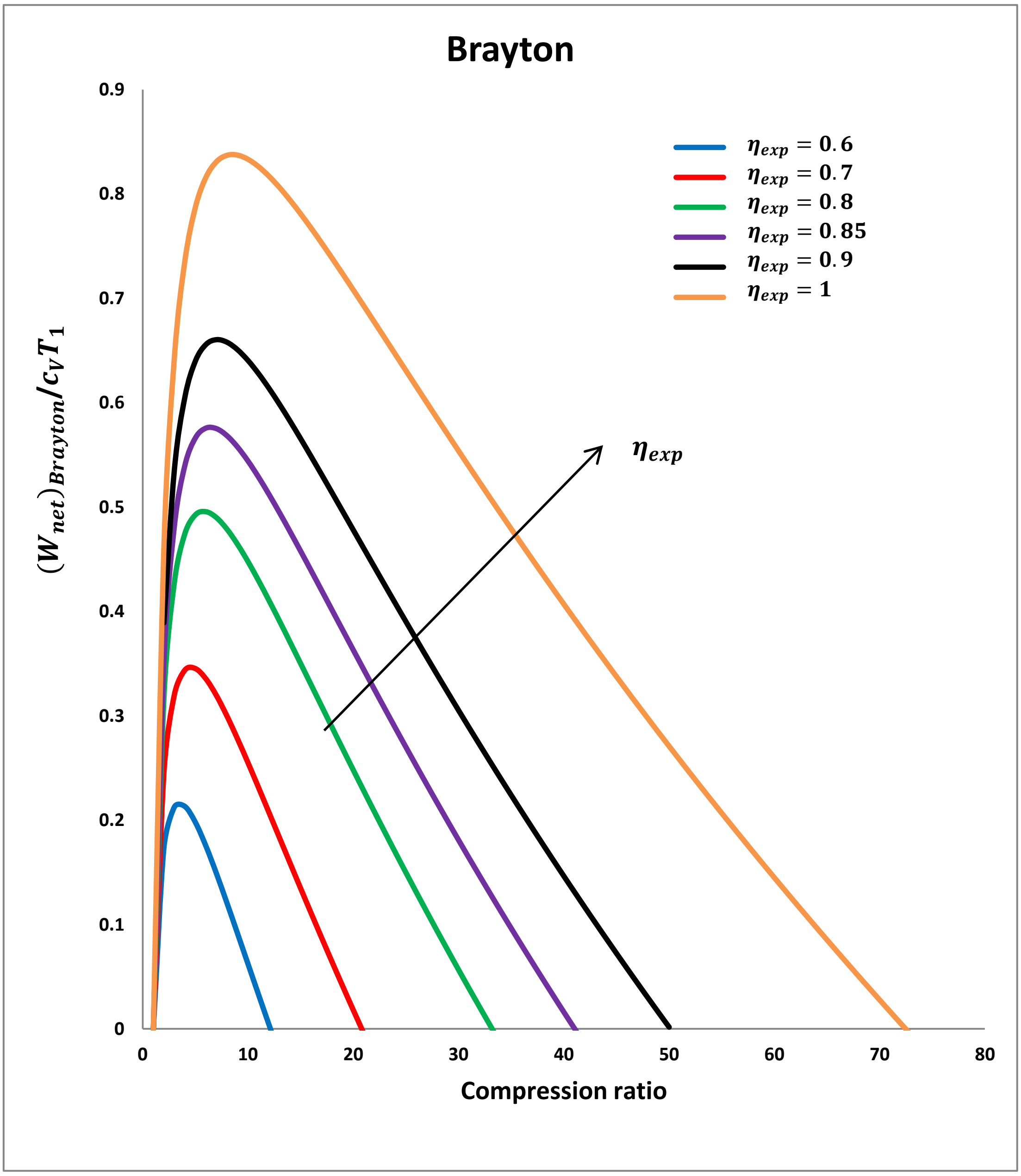

Figure 17 Variation of dimensionless work output $(W_{net})_{Brayton}/c_V T_1$ with compression ratio at different values of η_{exp}

As seen in a Fig.16 and Fig.17 as it was in Diesel cycle the thermal efficiencies and work outputs are close to zero at the compression ratio of 2, and then they increase with the compression ratio till they reach the maximum values, each at a certain compression ratio, then they decrease with an increase in the compression ratio.

The optimum compression ratio corresponding to maximum thermal efficiency and the maximum work output is increasing with the efficiency of compression. The maximum power output occurs at a pressure ratio less than the one which gives a maximum thermal efficiency.

Fig.18 shows that the maximum values of the entropy occur at small compression ratio value close to 1, and then they decrease with the compression ratio, for different η_{com}.

The entropy values are almost identical at low pressure ratio, and at high pressure an obvious discrepancies appear between them.

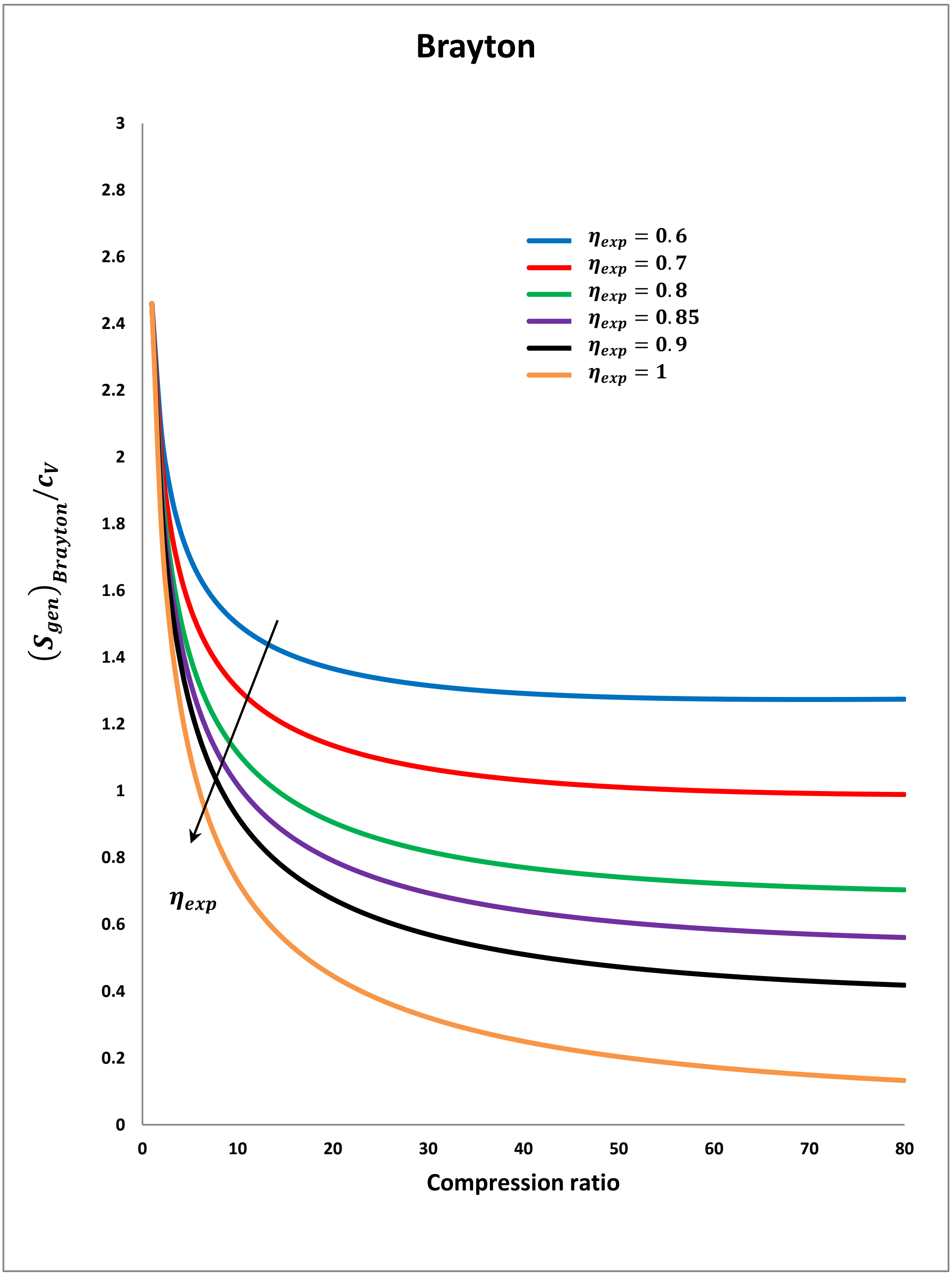

Figure 18 Variation of dimensionless entropy production $(S_{gen})_{Brayton}/c_V$
With compression ratio at different values of η_{exp}

4.5.1 Maximum thermal efficiency and maximum work out put for Brayton cycle at different values of the efficiency of expansion η_{exp}

η_{exp}	$\eta_{Brayton\_max}$	$Pressure\ ratio$	$(S_{gen})_{Brayton}/c_V$
0.6	0.087784	4	1.778
0.7	0.151512	6	1.47971
0.8	0.235414	9	1.15305
0.85	0.287042	12	0.95059
0.9	0.347729	15	0.76795
1	0.518865	31	0.31265

Table 9 Compression ratio and dimensionless entropy corresponding With Maximum thermal efficiency at different values of η_{exp}

η_{exp}	$(W_{net})_{max}/c_V T_1$	$Pressure\ ratio$	$(S_{gen})_{Brayton}/c_V$
0.6	0.21316	4	1.778
0.7	0.34528	5	1.55151
0.8	0.49564	6	1.31945
0.85	0.57577	6	1.23931
0.9	0.66048	7	1.08212
1	0.83731	9	0.78007

Table 10 Compression ratio and dimensionless entropy corresponding with Maximum dimensionless work out put at different values of η_{exp}

Tab. 9 and Tab. 10 show that the optimum compression ratio which corresponds to maximum thermal efficiency and the maximum work output increases with the efficiency of expansion. And the power output reaches the maximum value at pressure ratio less than the pressure ratio which corresponds to the maximum thermal efficiency.

At efficiency of expansion 60% the maximum thermal efficiency and the maximum work out put are reached at the same entropy and the same compression ratio.

At bigger values of efficiency of expansion the maximum thermal efficiency, the maximum work output, and the entropy increase with the efficiency of expansion each at certain value of compression ratio.

4.6 Impact of changing the efficiency of compression (η_{com}) on Brayton cycles

The changes of the thermal efficiency $\eta_{Brayton}$, dimensionless work output $(W_{net})_{Brayton}/c_V T_1$, and dimensionless entropy production $\left(S_{gen}\right)_{Brayton}/c_V$ were examined with the changes of compression ratio, and for $r_T = 4$, $\pi = 0.18$, $\gamma = 1.4$, $\eta_{exp} = 0.9$, $\eta_{com} = 0.6 \dashrightarrow 1$.

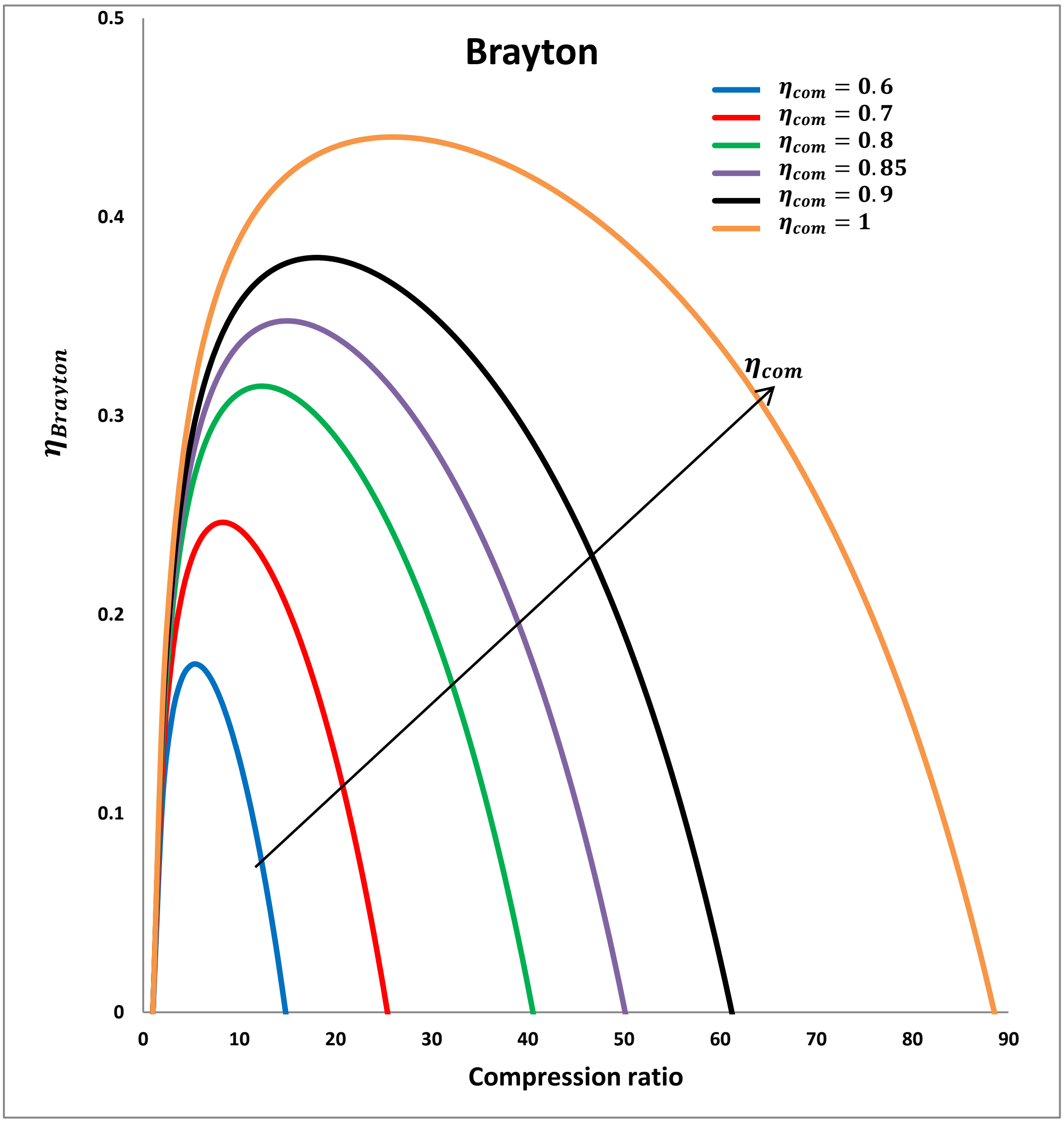

Figure 19 Variation of thermal efficiency $\eta_{Brayton}$ *With compression ratio at different values of* η_{com}

As seen in a Fig.19 the thermal efficiencies are zero at the compression ratio of 1, and then they increase with the compression ratio till they reach the maximum values, each at a certain compression ratio, then they decrease with an increase in the compression ratio till they reach zero again each at a certain compression ratio. The optimum compression ratio corresponding to maximum thermal efficiency increases with the efficiency of compression.

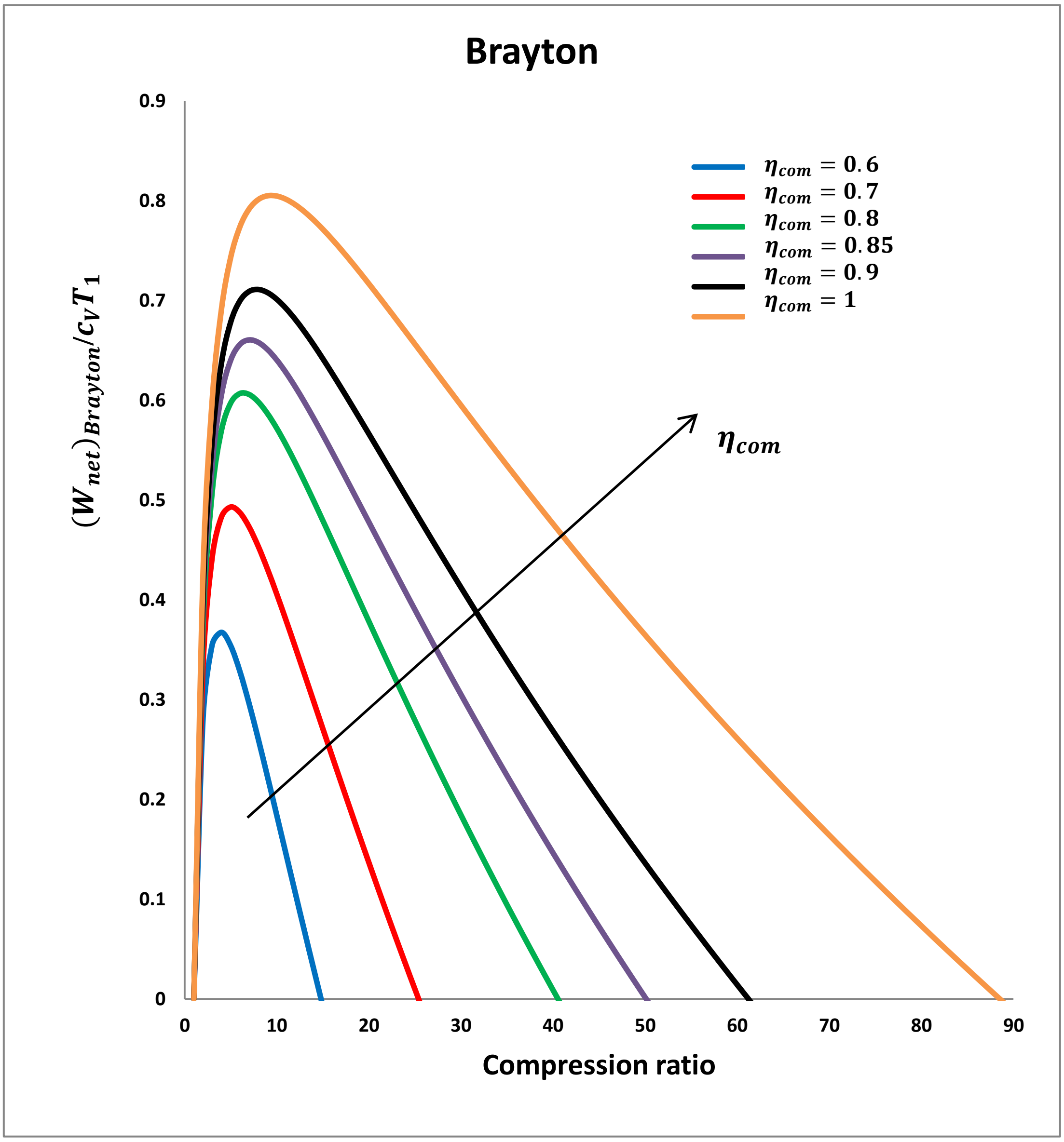

***Figure 20** Variation of dimensionless work output $(W_{net})_{Brayton}/c_V T_1$*

With compression ratio at different values of η_{com}

The last figure shows the changes of the work output at different values of compression‘s efficiency. It is zero for each of them at compression ratio of 1. Then it increases with compression ratio at each value of compression’s efficiency till it reaches its maxima, after that it starts to decrease in a faster way than it was for the thermal efficiency, the decrease continue with the compression ratio till it reaches zero again, each at a certain compression ratio.

The optimum compression ratio corresponding to maximum work output increases with the efficiency of compression. The maximum power output occurs at a pressure ratio less than the one which gives a maximum thermal efficiency.

The following figure (Fig. 21) shows the changes of entropy at different values of compression's efficiency. It starts at a maximum value which is corresponding to the compression ratio of 1, and then it starts to decrease with the compression ratio till it reaches constant value at compression ratio of about 15, the constant value of the entropy decrease with the efficiency of compression

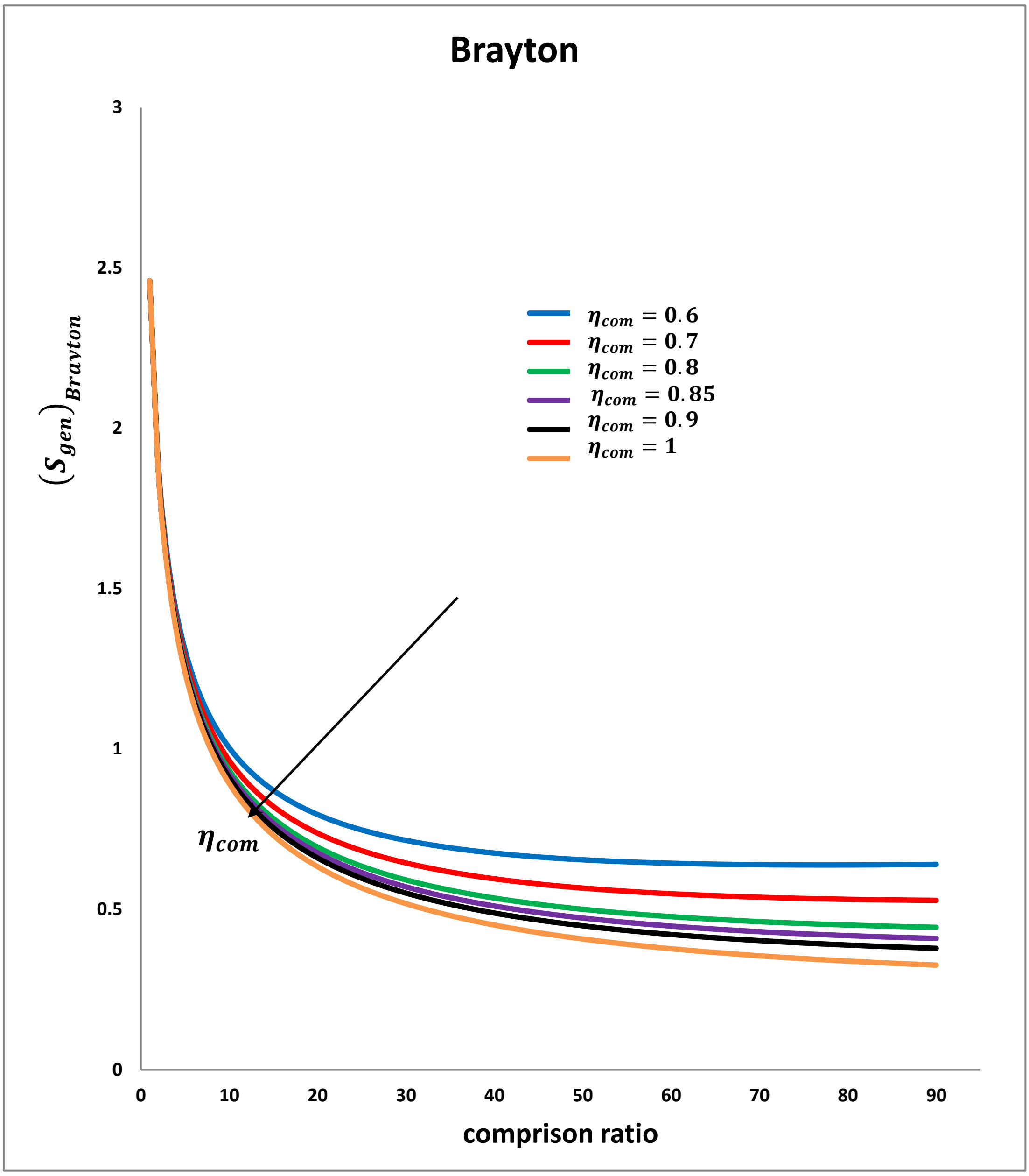

***Figure 21** Variation of dimensionless entropy production* $(S_{gen})_{Brayton}/c_V$
With compression ratio at different values of η_{com}

4.6.1 Maximum thermal efficiency and maximum work out put for Brayton cycle at different values of the efficiency of expansion η_{exp}

η_{com}	$\eta_{Brayton\_max}$	$Pressure\ ratio$	$(S_{gen})_{Brayton}/c_V$
0.6	0.174636	5	1.308132
0.7	0.246323	8	1.056019
0.8	0.314839	12	0.8626021
0.85	0.347729	15	0.7679496
0.9	0.379545	18	0.6931028
1	0.440192	26	0.5557527

Table 11 Compression ratio and dimensionless entropy corresponding With Maximum thermal efficiency at different values of η_{com}

η_{com}	$(W_{net})_{max}/c_V T_1$	$Pressure\ ratio$	$(S_{gen})_{Brayton}/c_V$
0.6	0.367389	4	1.42842
0.7	0.492986	5	1.28311
0.8	0.606749	6	1.16803
0.85	0.660483	7	1.08212
0.9	0.711031	8	1.00965
1	0.804961	9	0.93881

Table 12 Compression ratio and dimensionless entropy corresponding with Maximum dimensionless work out put at different values of η_{com}

Tab. 11 and Tab. 12 show that the optimum compression ratio which corresponds to maximum thermal efficiency and the maximum work output increases with the efficiency of compression. And the power output reaches the maximum value at pressure ratio less than the pressure ratio which corresponds to the maximum thermal efficiency.

5. Comparison between impact of increasing η_{exp} or increasing η_{com} compression efficiency on the thermal efficiency and the power output

The analysis has done depending on practical parameters ($r_T = 4$, $\pi = 0.18$, $\gamma = 1.4$, $\eta_{exp} = 0.9$, $\eta_{com} = 0.85$). The expansion and the compression efficiency were increased by 5%.

5.1 Otto cycle

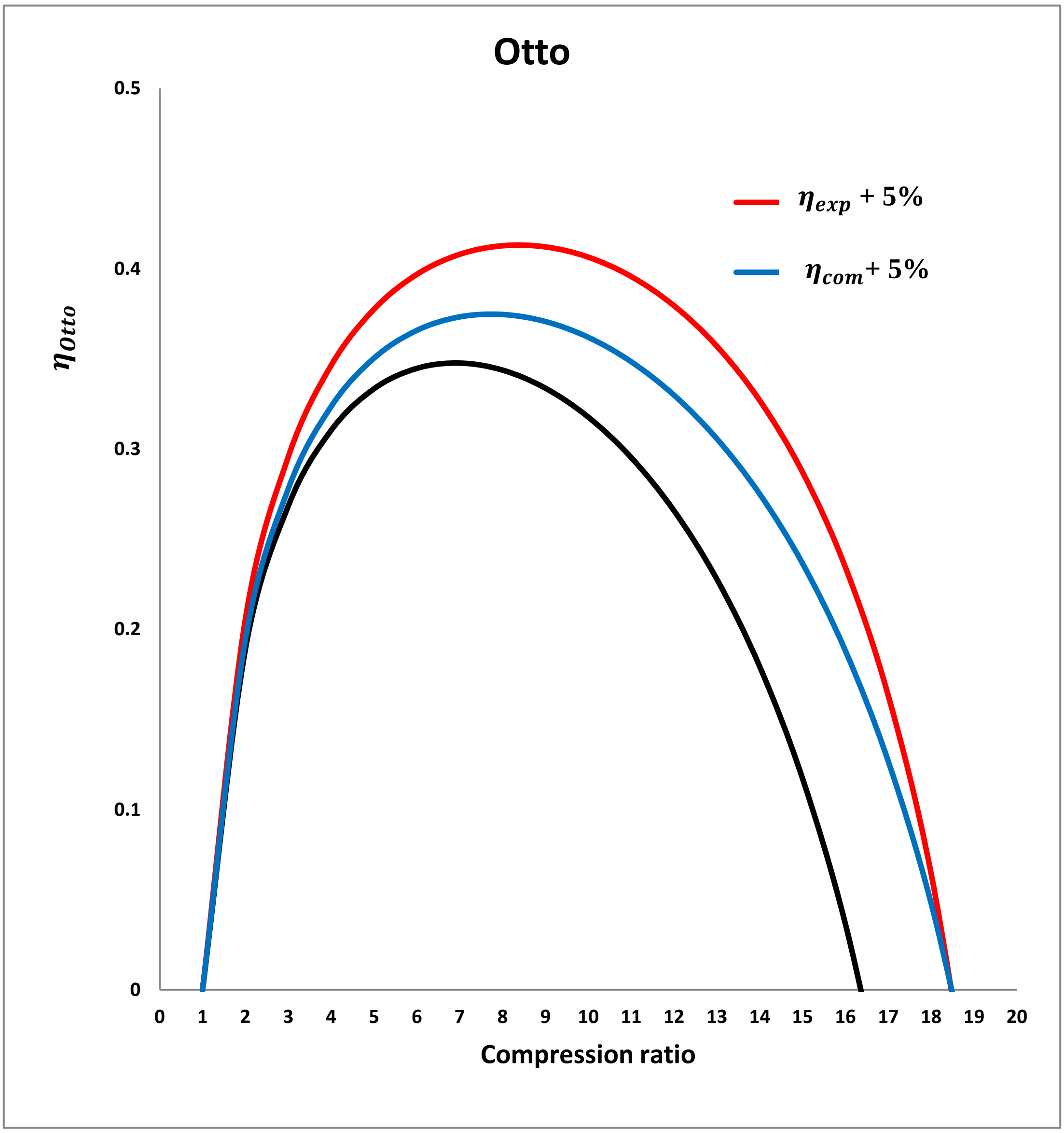

Figure 22 Impact of increasing η_{exp} and η_{com} on η_{Otto}

As Fig. 22 shows the changes of thermal efficiency in two cases, increase the efficiency of expansion, and increase the efficiency of compression. The difference between the new thermal efficiencies is zero at compression ratio 1, then it increases slightly till it reaches a maximum value, then it decreases and became smaller with the increase of compression ratio until it reaches zero again at compression ratio 18**.** One may realize that the impact of increasing η_{exp} is bigger than the impact of η_{com} on the maximum thermal efficiency is bigger as well at the same compression ratio.

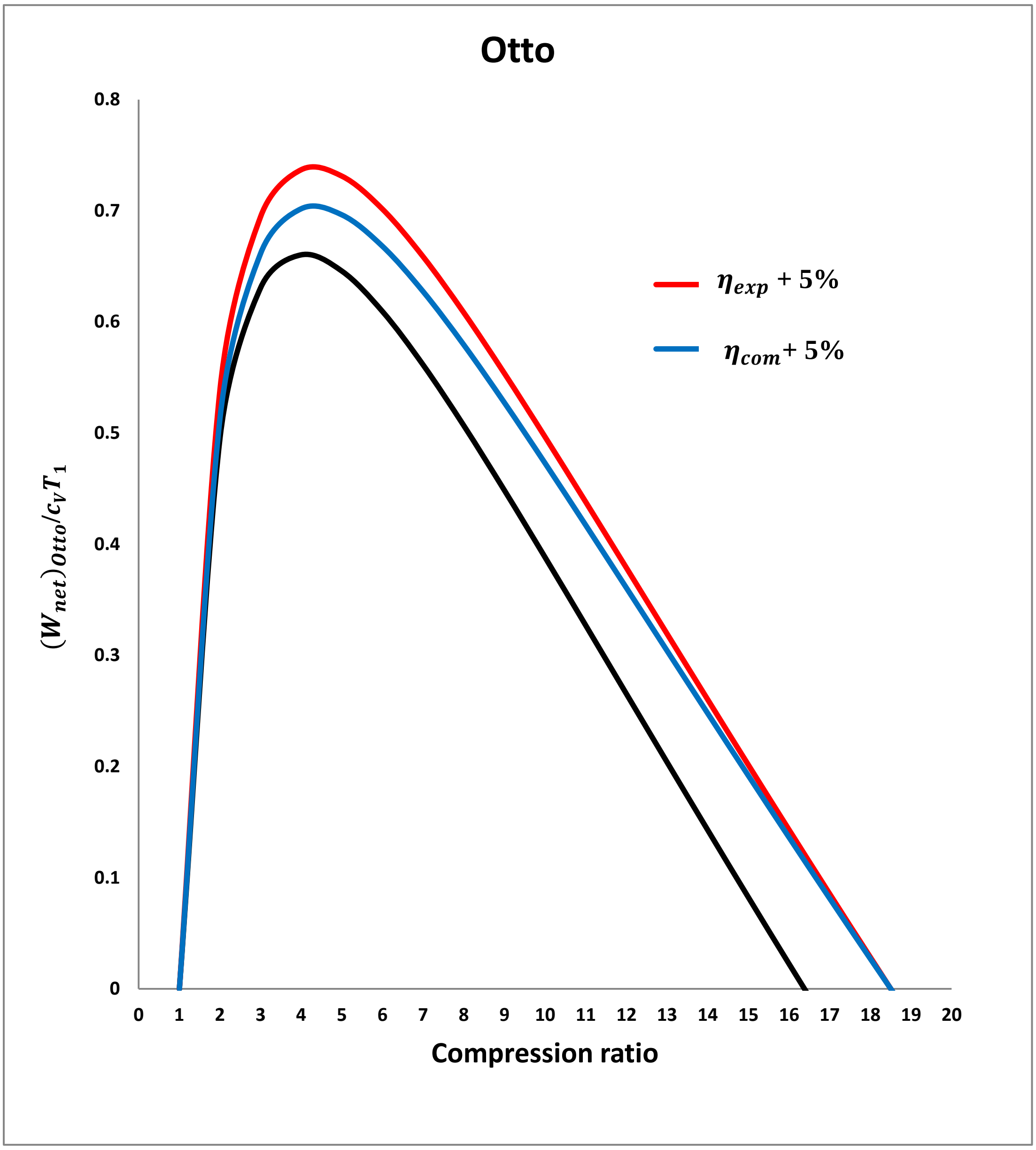

Figure 23 Impact of increasing η_{exp} and η_{com} on $(W_{net})_{Otto}/c_V T_1$

The above figure also shows that the impact of increasing of η_{exp} on the work output is bigger than the impact of η_{com}, and the maximum work output as we increase η_{exp} is bigger than the maximum work output which correspond to the increase of η_{com} at the same compression ratio.

The difference between the thermal efficiency in both cases is zero at compression ratio of 1, then at compression ratio 3 the difference increases slightly to reach its maximum value at compression ratio 4, then the difference decreases with the increase of compression ratio until they become equal at the same compression ratio 18 as we had for the thermal efficiency.

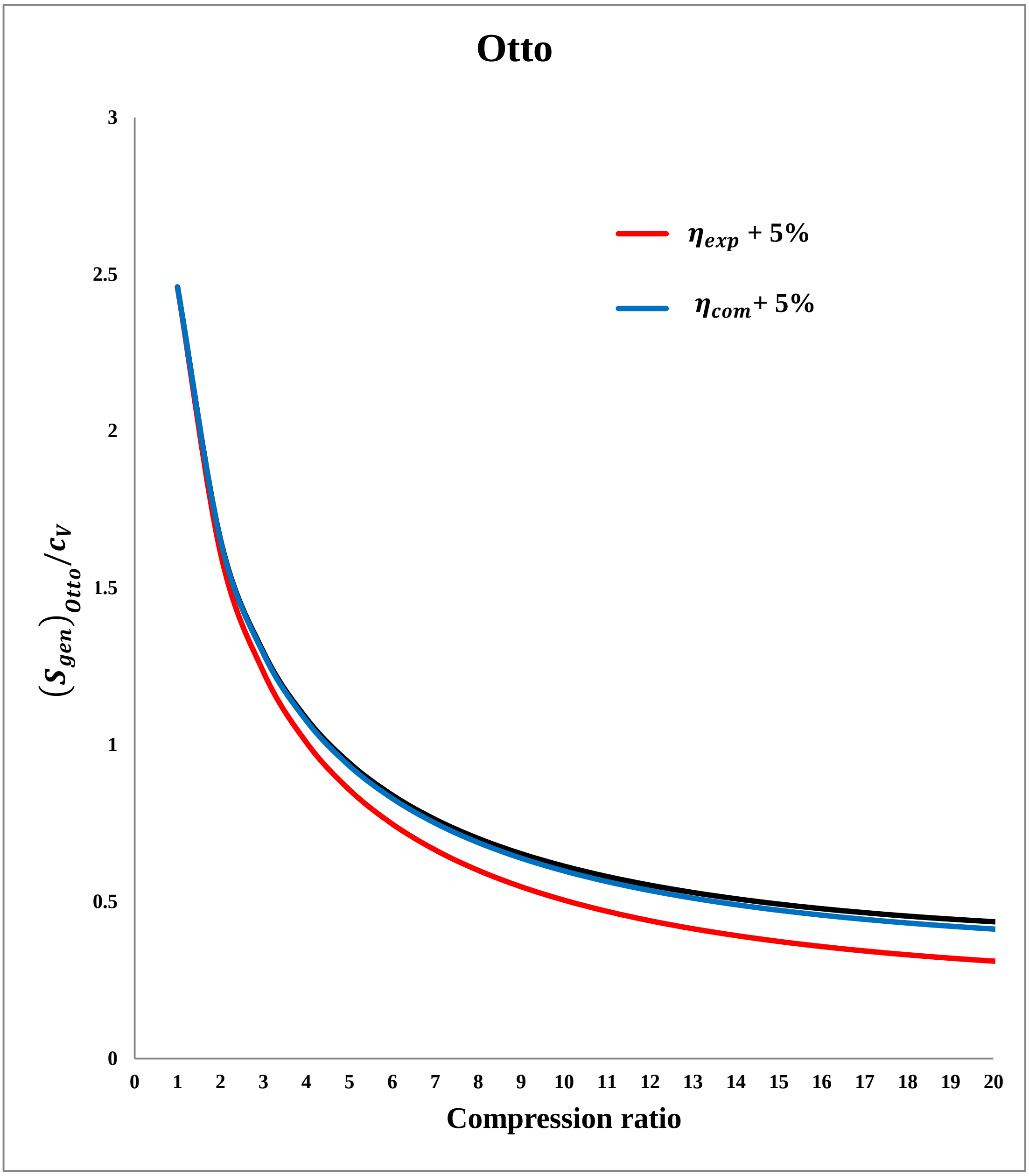

Figure 24 Impact of increasing η_{exp} and η_{com} on $(S_{gen})_{Otto}/c_V$

Fig. 24 shows that the entropy decreases when we increase the expansion efficiency or the compression efficiency.
At small compression ratio the entropy values are almost the same in both cases. But later at higher compression ratio the difference between entropy values increases till it reaches. Obviously one may notice that η_{exp} has bigger impact on the entropy than η_{com}.

5.2 Diesel cycle

Fig. 25 the difference between thermal efficiencies is zero at compression ratio of 2. Thermal efficiency increases by the impact of expansion efficiency more than the impact compression efficiency till they became identical at compression ratio 16.

But after that the effect is reversed, so at higher values of compression ratio (more than 16) the increase in compression efficiency has better effect on η_{Diesel}

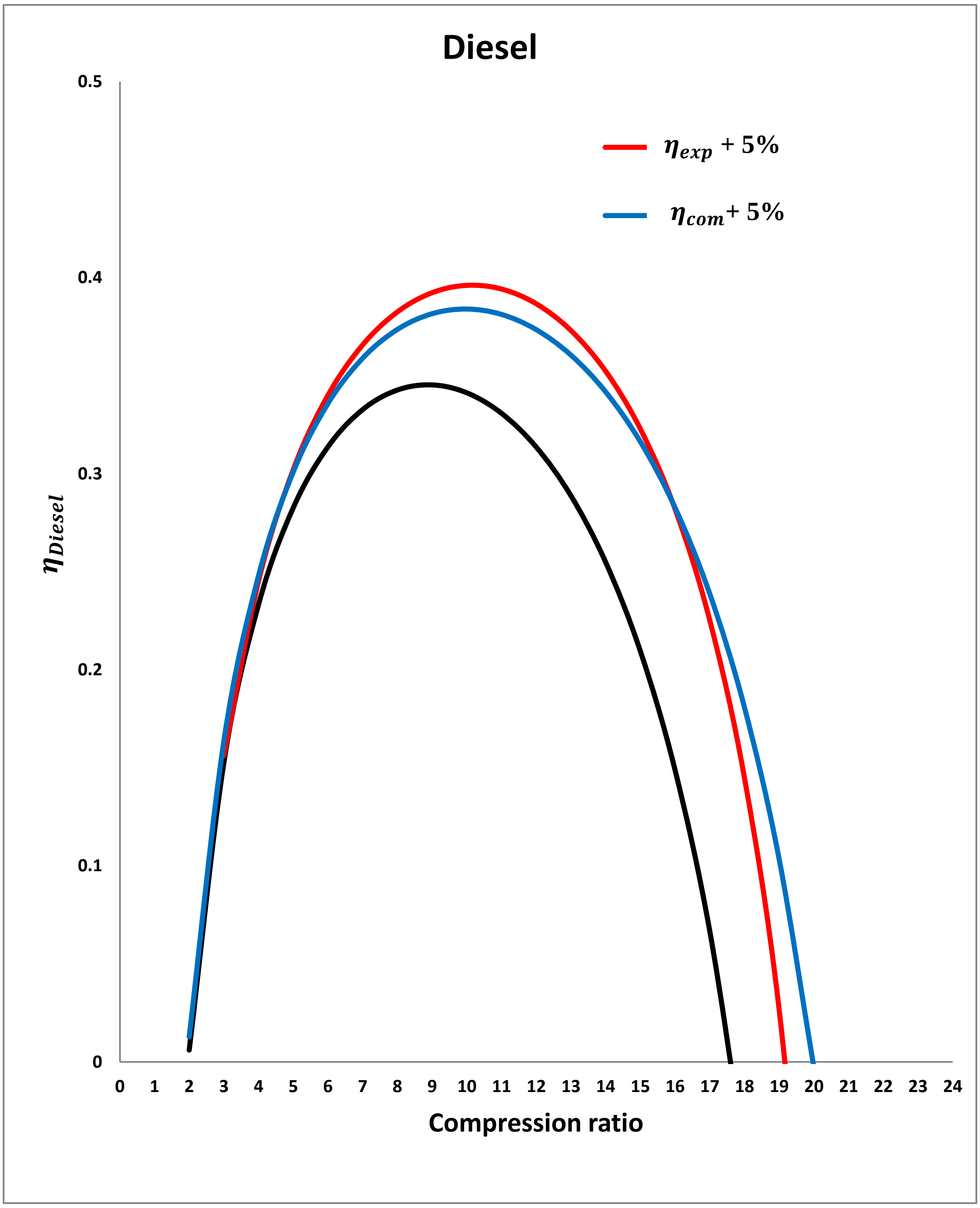

Figure 25 Impact of increasing η_{exp} and η_{com} on η_{Diesel}

Fig. 26 shows the effect on the work output. 5% increase of the efficiency of expansion leads to increase the power output till it reaches the maximum then it declines to reaches zero at certain compression ratio.

Increasing the efficiency of compression 5% also leads to increase the power output, but on low pressure ratio there is almost no effect on the power output, the effect appears on high pressure, and it is bigger than the effect of η_{exp} on high pressure ratio.

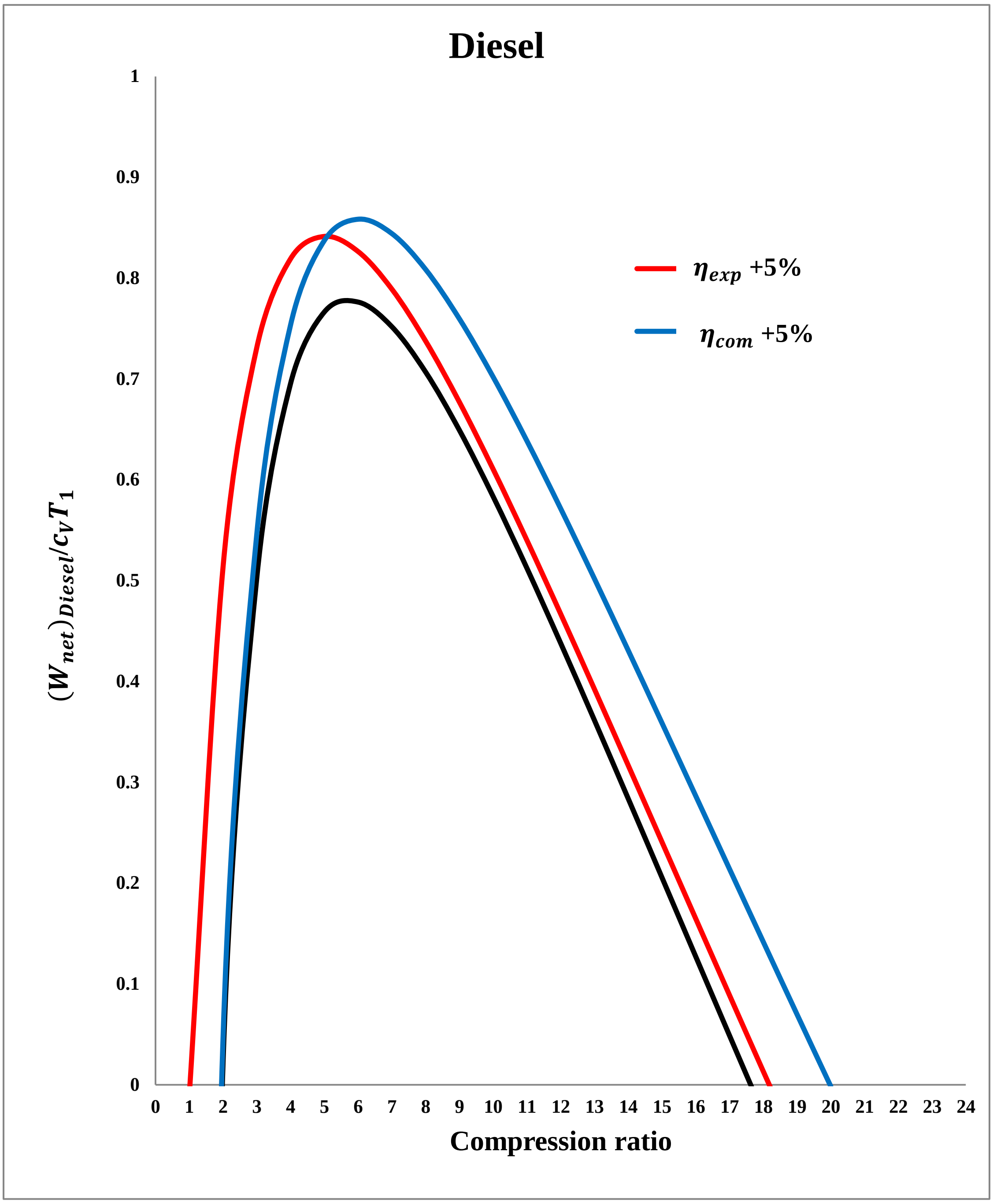

***Figure 26** Impact of increasing η_{exp} and η_{com} on $(W_{net})_{Diesel}/c_V T_1$*

Fig. 27 shows that the entropy decreases when we increase the expansion efficiency or the compression efficiency.

At small compression ratio the entropy values are almost identical and they rapidly decrease with the compression ratio. At higher compression ratio there is a little discrepancies between them and they decrease slowly with the compression ratio. Obviously one may notice that η_{exp} has bigger impact on the entropy than η_{com}.

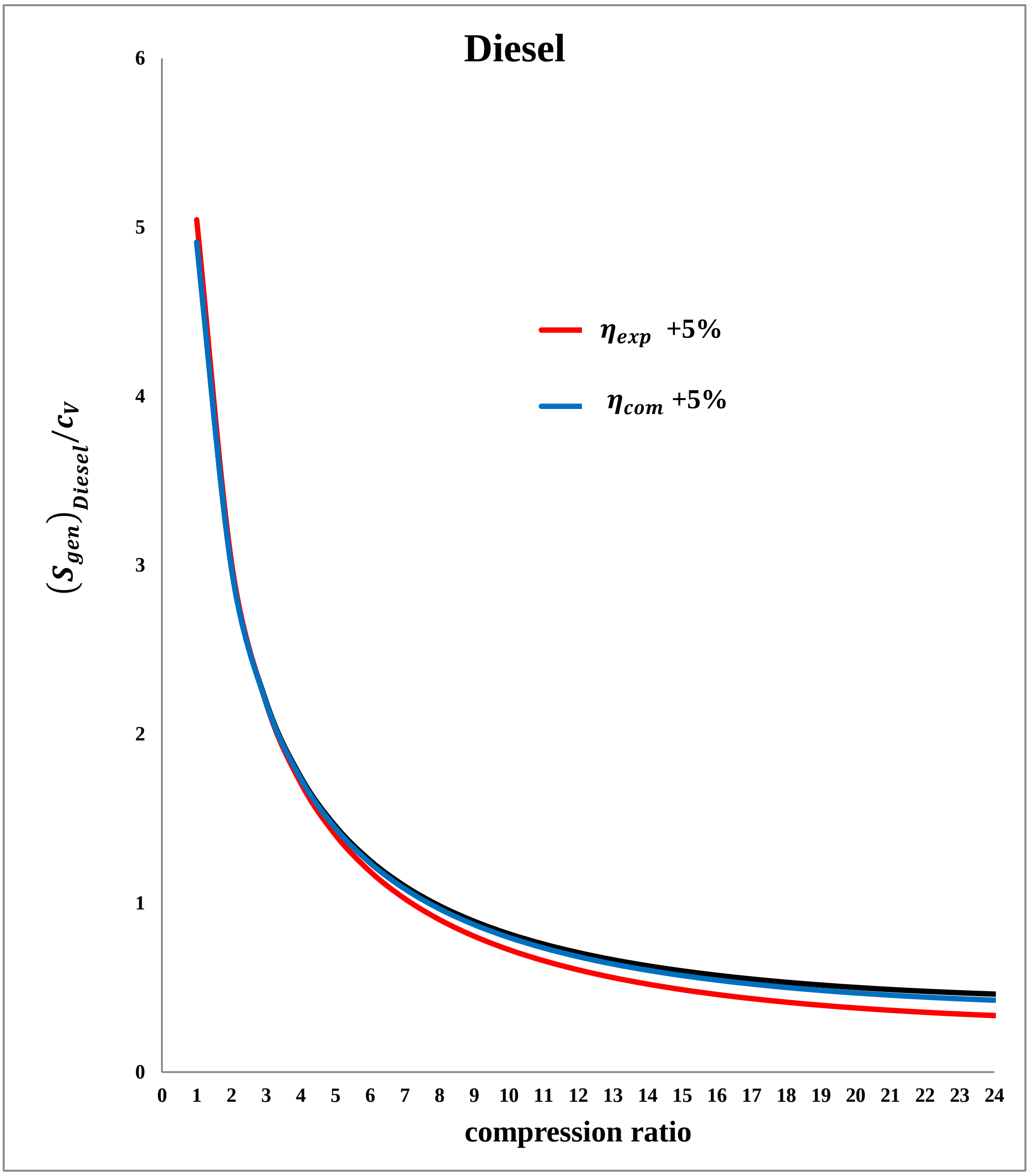

Figure 27 Impact of increasing η_{exp} and η_{com} on $(S_{gen})_{Diesel}/c_V$

5.3 Brayton cycle

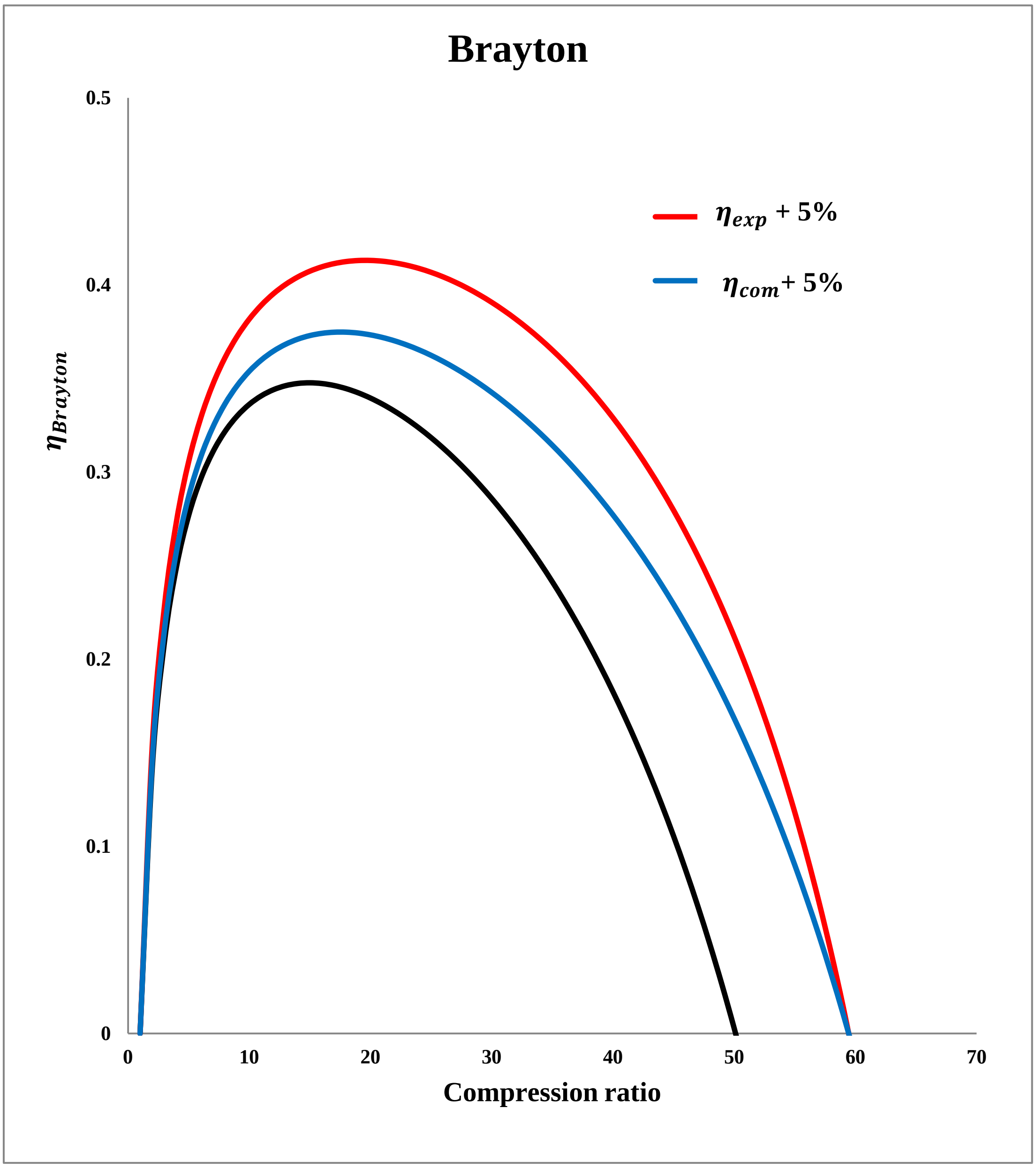

Figure 28 Impact of increasing η_{exp} and η_{com} on $\eta_{Brayton}$

In Brayton cycle we notice that the effect is similar to Otto cycle. As the thermal efficiency starts from zero (Fig. 28), then it reaches the maximum value, beyond which declines till it reaches zero at certain compression ratio.

The maximum of thermal efficiency which result from increasing the efficiency of expansion is bigger than the maximum thermal efficiency result from increasing the efficiency of compression.

The power output changes are similar to the thermal efficiency changes, as it is shown in Fig.29. The impact of expansion‘s efficiency on the maximum power output is bigger than the impact of compression’s efficiency at the same compression ratio.

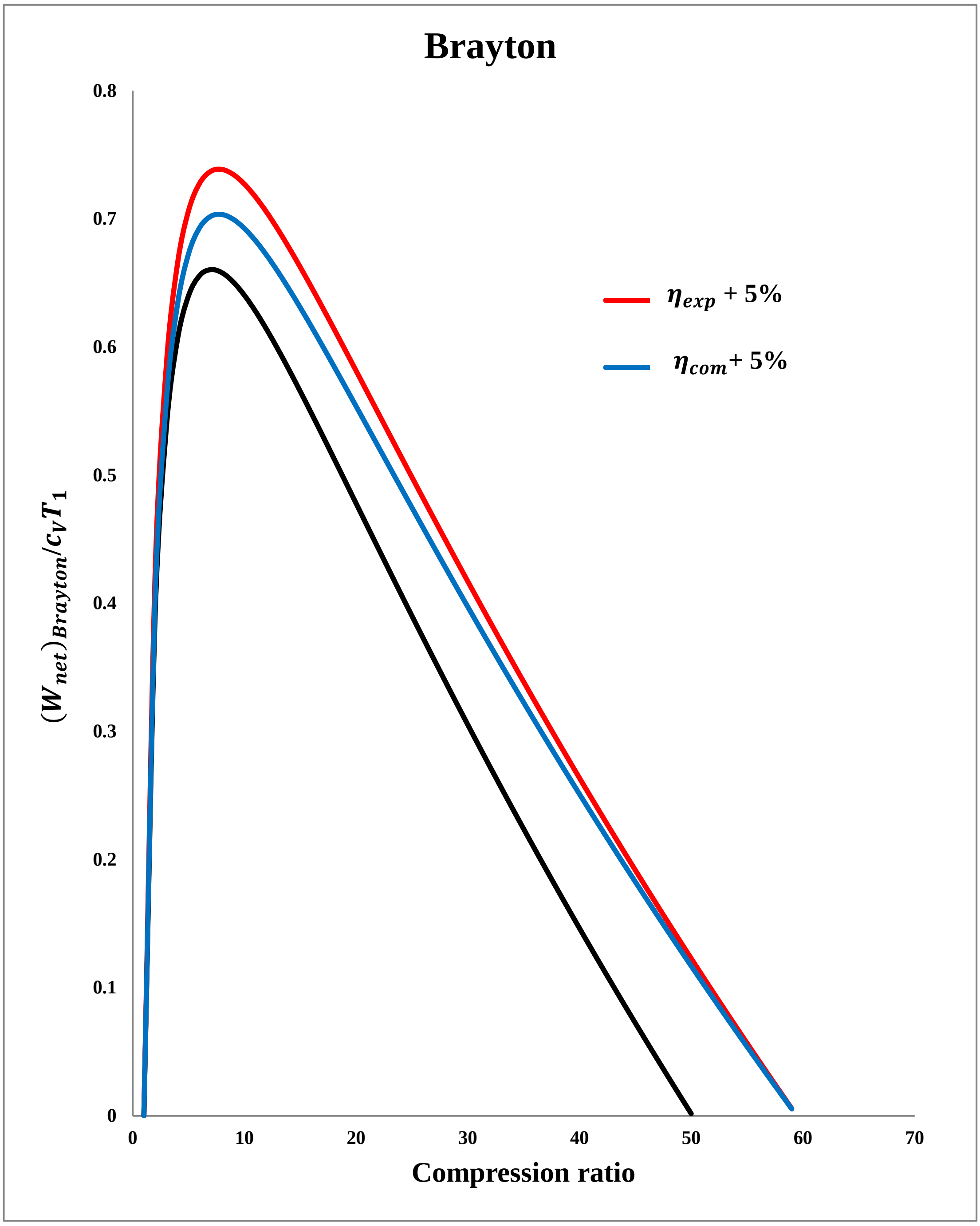

Figure 29 Impact of increasing η_{exp} *and* η_{com}*on* $(W_{net})_{Brayton}/c_V T_1$

Fig. 30 shows that the entropy decreases when we increase the expansion efficiency or the compression efficiency for Brayton cycle.
At small compression ratio the entropy values are almost identical and they rapidly decrease with the compression ratio. At higher compression ratio there is a little discrepancies between them and they decrease slowly with the compression ratio. The compression ratios are obviously bigger than it was for Diesel and Otto cycle.

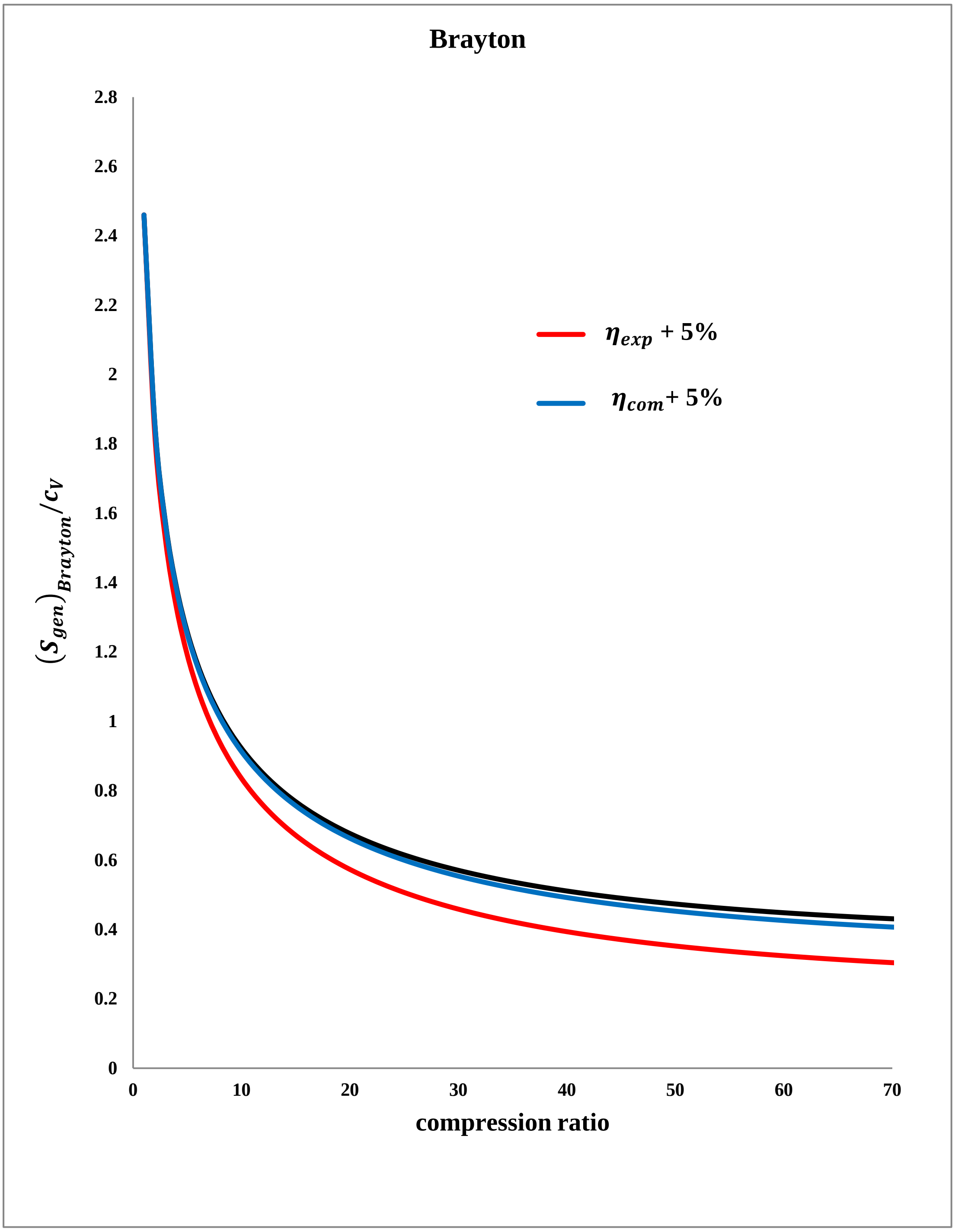

Figure 30 Impact of increasing η_{exp} and η_{com} on $(S_{gen})_{Brayton}/c_V$

6. Conclusion

The main goal of this thesis was to examine the three known types of heat engine, and to investigate Otto, Diesel and Brayton cycles experiencing external and internal irreversibilities to investigate the work output, the thermal efficiency, and the entropy at different values of efficiency of expansion and compression**.**

Examine the changes of thermal efficiency, and power output, and entropy show that they have similar trend for all engines at different values of efficiency of expansion and compression, and the maximum work output is reached at smaller compression ratio than maximum of thermal efficiency.

It is shown in this study that 5% increase of practical efficiency of expansion leads to optimize the cycle by increasing the thermal efficiency and the work output, and by decreasing the entropy at the same time. The effect of this optimization is bigger than the effect of optimization if we increase the efficiency of compression 5%. So it is better to have higher efficiency of expansion because it has bigger impact than the impact of compression's efficiency,

The efficiency of compression should be more than 80%, and the efficiency of expansion should be more than 90% to get the best performance with the minimum entropy production.

Despite the fact that we have found out that the heat engine at minimum entropy production which is identical with maximum efficiency and maximum work output at expansion's efficiency or compression efficiency of 60%, the It appears that the minimum entropy production criterion as defined in the work cannot be considered as a useful kind of optimization, because it does not correspond all the time with the maximum thermal efficiency and maximum work output.

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